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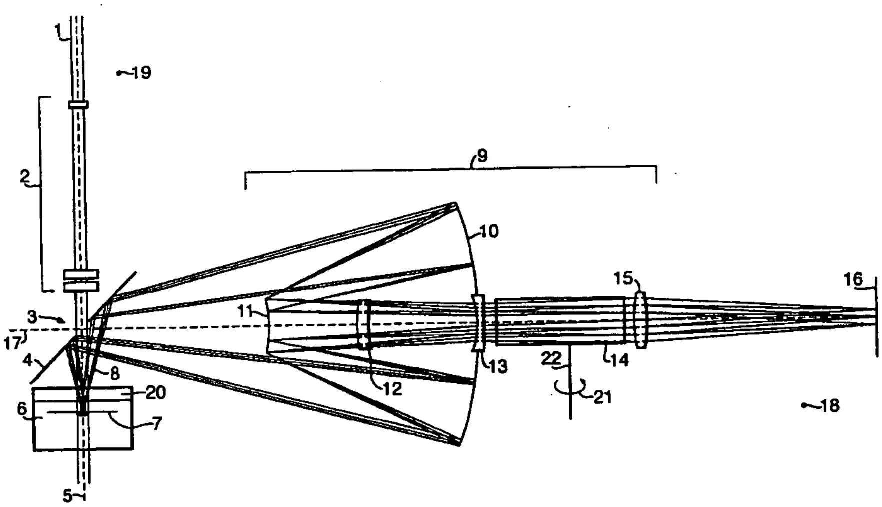

(57) Abstract: A spectral analysis interface comprises illumination optics (2) to focus light from a narrow band source onto a sample (6); collection means for collecting incident light scattered from the sample; and input means to input the collected light to a spectral analysis device; wherein the illumination optics (2) focuses the light to a line or point focus; wherein the input means comprises refracting components (12, 13, 15); wherein the collection means comprises a primary reflector (11) and a secondary reflector (10) such that the arrangement of the primary and secondary reflectors gives rise to a central obscuration; wherein illumination of the sample is within the region obscured by the central obscuration; and wherein the collection means projects a real image of the illuminated region of the sample to the input means; wherein the input means projects a real image of the illuminated region of the sample to the spectral analysis device; and whereby substantially full chromatic aberration correction is maintained at the spectral analysis device over a range of illumination wavelengths without the need to change the relative positions of any of the components of the collection means or input means.

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CATADIOPTRIC OPTICAL RELAY SYSTEM FOR SPECTROMETERS

This invention relates to an spectral analysis interface, in particular for interfacing to a spectrometer.

When attempting to study scattering, emission or reflectance using a tuneable laser that can cover a very large spectral bandwidth in narrow steps, the limiting experimental factor encountered is the maintenance of good optical focus. This is critical, as poor focus leads to poor signal collection efficiency, which in turn leads to reduced precision and accuracy in the collected data. This is because of the degradation in signal-to-noise ratio and can only be recovered by an increase in experimental time and/or an increase in excitation power. A spectrometer can be used with a line focus or a point focus. It is standard practice to use a line focus which reduces the power incident on a particular point, so avoiding damage to delicate samples.

Previous designs for transfer optics have used simple lens arrangements. However, these do not maintain focus as a function of wavelength. Alternatively, mirror optics have been used which produce good focus as a function of wavelength, but only at the centre of field; off axis, aberrated images are produced, so mirrors cannot be used with a long slit, only for a point focus.

For the purpose of this application, the term catadioptric means an optical system comprising a combination of one or more mirrors and one or more lenses; the term achromatic means aberration correction at two discreet wavelengths across the operational waveband; the term apochromatic means correction at three discreet wavelengths across the operational waveband.

Examples of prior art imaging systems include US5493443 which relates to a lens for a FT-Raman microscope using an all mirror collection optic, which is limited to point image collection and US4591266 which relates to a parabolic focusing apparatus for optical spectroscopy using an all mirror collection / illumination optical system, which is limited to point area sampling. Another document, US5917594, describes a spectroscopic measurement system using an off-axis spherical mirror and refractive elements. This is a catadioptric collection illumination design that provides achromatic correction, but is only directed to point sampling.

Documents US5717518 and PCT\US98\16568 describe catadioptric systems intended for imaging type applications in the ultraviolet. They offer broadband performance, but with a maximum bandwidth limited to 200nm. The designs have a numerical aperture greater than ~0.7 which is equivalent to F/0.5. The consequence

of using a large numerical aperture collection optic to couple light into a spectrometer is that a large magnification factor results and hence light is collected from only a small region on the sample. This is both unsuitable and undesirable for many spectroscopy applications in particular due to the small illumination region on the sample. For example, the high intensity due to concentration of the illumination within a small area may cause the destruction of a sensitive sample under test. These optical systems are very complex in order to achieve the high imaging performance. Such complexity is inappropriate for the problem addressed by the present invention.

In accordance with the present invention, a spectral analysis interface comprises illumination optics to focus light from a narrow band source onto a sample; collection means for collecting incident light scattered from the sample; and input means to input the collected light to a spectral analysis device; wherein the illumination optics focuses the light to a line or point focus; wherein the input means comprises refracting components; wherein the collection means comprises a primary reflector and a secondary reflector such that the arrangement of the primary and secondary reflectors gives rise to a central obscuration; wherein illumination of the sample is within the region obscured by the central obscuration; wherein the collection means projects a real image of the illuminated region of the sample to the input means; wherein the input means projects a real image of the illuminated region of the sample to the spectral analysis device; and whereby substantially full chromatic aberration correction is maintained at the spectral analysis device over a range of illumination wavelengths without the need to change the relative positions of any of the components of the collection means or input means.

The present invention forms a line or point focus on the sample, collects light scattered from the line or point focus and inputs this light into an analysis device, such as a spectrometer. The invention maintains the line or point focus of the collected light at a substantially fixed location in or on the sample as a function of wavelength over the full operational wavelength range, according to which is required for applications such as Raman or fluorescence spectroscopy. Another benefit of the device is that imaging can be performed simultaneously over all wavelengths. This functionality facilitates quantitative scattering measurements to be made from absorbing species within a well defined measurement volume, with substantially no intervention in the collection and input means, and minimal intervention in the illumination means.

Line focussing is advantageous for many scattering and emission techniques. For sensitive samples, a line focus is a preferred way of getting energy onto or into a sample because the energy is spread over a larger area thereby reducing the likelihood of localised damage occurring to the sample. Line focussing can also be advantageous for performing measurements on samples with a higher damage threshold: in this case a higher photon flux than that used for point focussing may be employed without the risk of damage occurring to the sample. The operational advantages include an improved signal to noise ratio and hence a reduction in the required measurement time. A point focus is required when high optical powers are specifically desired or when a measurement is required with high spatial resolution.

To obtain the benefits of a line focus, the whole line must be imaged into the analysing device and the whole image used at the detector. This is made possible by the collection means and input means, which together form a catadioptric design. This type of design minimises the number of optical components required and overcomes optical aberration. Aberration correction is achieved without necessary inclusion of an intermediate image.

The system can also be adapted to focus to a point or a line and image onto an area. This may be desirable for some spectroscopy applications.

The interface can operate over a range of illumination wavelengths from the ultraviolet to the infra red, but preferably, the range of illumination wavelengths spans at least 200nm and includes within the range 250nm and 393nm.

More preferably, the range of illumination wavelengths spans at least 500nm and includes within the range 250nm and 693nm.

Preferably, the illumination optics comprises either cylindrical or spherical focussing optics to produce a line or point focus respectively.

The incident light may be produced by any source that gives rise to electromagnetic radiation within the wavelength passband of the optical system, but preferably the light source is monochromatic with or without a predetermined polarisation, comprising one of a discharge lamp, a filament lamp, a semiconductor source such as a light emitting diode, a single line laser, a multiline laser, a tuneable laser or a plurality of tuneable lasers.

One example of a suitable source is a high power ArF eximer laser which produces UV radiation with a wavelength of 193nm.

Suitably, the collection means further comprises a turning mirror to reflect scattered light from the sample onto the primary reflector. Unless polarisation

information is required, none of the components in the collection means or input means need to be moved to operate over the full wavelength range.

The incident light may pass through the sample or be reflected from it. Preferably, the light is collected in the back-scattered direction. This arrangement collocates the illumination focus plane and collection focus plane within the sample so that the operation is self aligning and substantially unaffected by sample thickness; moreover, this arrangement enables easy co-location to be achieved over a wide waveband of operation.

Preferably, the incident light is incident on the sample through an aperture in the turning mirror. This avoids damage to any of the components in the way of the illuminating beam.

Preferably, the aperture in the turning mirror is so positioned such that any stray scattered light caused by the presence of this aperture is blocked by the central obscuration formed by the secondary mirror in the collection means. The blocking of this light prevents the light from being incident at the spectral analysis device, thereby avoiding adversely affecting the performance of the said device, by for example causing damage. Stray light may be caused, by for example, illumination light being incident on the sides of the aperture.

An alternative illumination means may comprise a prism or small mirror to reflect illumination onto the sample; wherein the prism or small mirror is so positioned that stray light scattered by the prism or small mirror is prevented from reaching the spectral analysis device by the obscuration formed by the secondary mirror of the collection means.

For the purposes of this application, the F-number of an optic is its focal length divided by its diameter. A small F-number corresponds to a large focus cone angle.

Preferably the F-number of the focussed illumination light is small so as to be closely matched to the collection means F-number, thereby ensuring efficient collection of light scattered from the focus region of the illumination light. Preferably the minimum F-number of the illumination is limited by the size of the obscuration of the secondary mirror of the collection means

Preferably, the primary reflector comprises a reflecting concave mirror, the secondary reflector comprises a reflecting convex mirror and the input means comprises at least one lens. Alternatively, the collection means further comprises one or more refracting optical elements that are preferably weakly refracting, one or more of which may be in optical contact with the primary or secondary reflector.

Preferably the real image of the illuminated region of the sample, projected by the collection means to the input means, retains small spherical aberration; and the input means projects a real image of the illuminated region of the sample, and compensates the said small spherical aberration; such that there is minimal compensation of spherical aberration between the collection and input means.

Preferably, the device further comprises an analysing element. Suitably, the analysing element has optical characteristics that it transmits light and has substantially no effect on focus; wherein the aberration correction at the spectral analysis device is maintained for moderate rotation angles of the analysing element; wherein rotation of the analysing element results in the utilised areas of the refracting and reflecting components in the collection means and input means, to translate across the respective surfaces of the input means and collection means; wherein this translation causes small lateral offsets between the spherical aberration in different parts of the optical system; and wherein decentred compensation of spherical aberration induces minimal axial coma.

Preferably, the analysing element comprises a polariser, compensating block, prism or wavelength filter. The polariser may comprise one or more prisms that are made of suitable birefringent materials, for example, α - barium borate, quartz, or magnesium fluoride. The incorporation of a polariser facilitates spectral discrimination by polarisation state and enables an optimum and well defined polarisation state input to the analysing device.

The analysing element may be at a fixed angle, or rotated to enable wavelength operation over the full required waveband.

Preferably, the analysing element is rotated to tune its transmission properties. The rotation introduces substantially no significant aberrations.

Preferably, the interface further comprises a baffle such that substantially only light from close to the focus is input to the analysis device. This baffle is particularly appropriate when using line type illumination at the sample and measurement is required with optimum depth discrimination, for example, when performing measurements within a sample, or on the surface of a translucent sample. The illumination means focuses light on or within the sample. In normal mode of operation, without the baffle in place, the collection means and input means couple light to the spectral analysis device that originates from both the focus region of the illumination means as well as from the out of focus region. The purpose of the baffle is to significantly reduce the coupling of light from the out of focus region. Preferably, the baffle is located near to the secondary mirror. The baffle operates by

substantially blocking collection of scattered light from regions of the sample through which illumination light transits on passage to the line focus region.

Preferably, the analysis device comprises one of a spectrometer, a point detector, a one-dimensional detector array? or a two-dimensional detector array.

The invention will now be described by way of example only with reference to the following drawings in which;

Figure 1 is a schematic diagram of an optical system interface in accordance with the present invention that is suitable for use with a spectrometer;

Figure 2 illustrates different ways of providing an input to an analysis device for the interface of Fig. 1

Figure 3 illustrates the illumination optics of Fig. 1 in more detail.

Figure 4 is a graph of the separation of the illumination optics against the excitation wavelength for the interface of Fig. 1;

Figure 5 illustrates in more detail different examples of illumination optics for use in the optical imaging interface of Fig. 1;

Figure 6 illustrates the concept of meridional and sagittal aberrations in an optical system;

Figure 7 illustrates the concept of paraxial longitudinal aberration in an optical /system;

Figure 8 illustrates the concept of wavefront aberration in an optical system;

Figure 9 illustrates the concept of the line spread function;

Figures 10a to 10c illustrate the collection optics line spread function at 400nm, 220nm and 700nm respectively at the slit centre in an interface as described in Fig. 1;

Figures 10d to 10f illustrate the collection optics line spread function at 400nm, 220nm and 700nm respectively over the full slit height of an interface as shown in Fig. 1;

Figure 11 shows a comparison between the line spread function of the collection optics and a region typically illuminated by an incident laser beam;

Figures 12a to 12c illustrate transverse ray aberrations for 2, 3 and 4 lens collection optics designs respectively for use in an interface according to the invention;

Figure 13 illustrates paraxial chromatic aberration for the 3 lens collection optics design for use in an interface according to the invention;

Figure 14 illustrates optical wavefront plots for the 3 lens collection optics designs respectively for use in an interface according to the invention;

Figures 15a to 15c illustrate transverse ray aberrations for the 3 lens collection optics design for use in an interface according to the invention, with the polariser tilted at 0°, 1° and 2° respectively;

Figure 16 illustrates the concept of side lobe leakage between side lobes of the Rayleigh and Raman scattered light; and

Figure 17 shows the effect of light coupling between the illumination and collection optics of the interface of Fig. 1.

Fig.1 shows an example of an interface according to the invention. An incident beam of light 1 from a laser source (not shown) is focussed by a set of illumination optics 2, through an aperture 3 in a turning mirror 4, which in this example is set at 45° to an optical axis 5 of the illumination optics 2 and is incident on a sample 6. The illumination optics 2 may be cylindrical, in which case the incident light is focussed to a line 7 on or within the sample, or spherical, in which case the light is focussed to a point on or within the sample. The incident light is generally narrowband, rather than pure monochromatic, but the illumination optics operate with either. Light 8 scattered by the sample 6 is reflected by the turning mirror 4 into a catadioptric collector 9. The light entering the catadioptric collector 9 is collected by a large concave mirror 10 and is directed by a secondary reflector 11 through two lenses 12,13 and a polariser 14. The polariser is made of a birefringent material, although materials which are not birefringent could be used. The lenses 12,13 serve to collimate the light inside the polariser 14. A third lens 15 focuses the light to a plane 16 at the input of an analysis device, in this case a spectrometer slit.

The collection optical axis 17 is defined such the centres of curvatures for all optical surfaces between the turning mirror 4 and spectrometer slit 16 lie on the axis 17; and that the collection optical axis intercepts the spectrometer slit 16. There is an option, as described later, that the polariser 14 is not necessarily orientated along axis 17.

The turning mirror 4 rotates the direction of the optical axis 17. This rotated direction defines axis 5. A base plane 18 is defined such that it contains both the optical axis 17 and the long axis of the spectrometer slit 16.

In the case of spherical illumination optics 2 being used, the centres of curvatures for all optical surfaces of the illumination optics 2 lie on the axis 5. The focus of the illumination optics is coincident with the focus plane for the collection optics. In the case of cylindrical lenses being used, the centres of curvatures of the illumination optics lie on a single plane 19. Optical axis 5 lies within plane 19. Planes

18 and 19 may or may not be coincident. The line focus 7 lies in plane 18, and line 7 and the spectrometer slit 16 lie in conjugate planes of the collection optics 9.

The orientation of the turning mirror 4 dictates the relative orientation of the axes 5 and 17. The turning mirror 4 is preferably orientated at 45° to the collection optical axis 17. The optical system interface may, however, still be operated if the turning mirror 4 is not so orientated after necessary re-alignment and possible re-design of various optical components.

Measurements are made by positioning the measuring device at plane 16. Suitable measuring devices include a spectrometer, in which case 16 coincides with the entrance slit of the spectrometer, or an imaging detector such as a CCD device.

The use of one or more additional measuring devices for either simultaneous measurements, or sequential measurements can be achieved using optical arrangements such as illustrated in Fig.2. This shows a side view of the collector optics, between lens 13 and plane 16.

The insertion of a beam director 47 between lens 15 and plane 16 enables an additional measuring device to be located at plane 16a. Here plane 16a is an image plane that is substantially equivalent to plane 16.

The insertion of a beam director 47' between polariser 14 and lens 15 enables the light to be directed through lens 15b which serves to image the light on an additional measuring device located at plane 16b. Here plane 16b is an image plane that is substantially equivalent to plane 16. Of course there may be magnification differences dependent on the focal lengths of lenses 15 and 15b.

The insertion of a beam director 47" between lens 13 and polariser 14 enables the light to be directed through lens 15c which serves to image the light on an additional measuring device located at plane 16c. Here plane 16c is an image plane that is substantially equivalent to plane 16. As before, there may be magnification differences dependent on the focal lengths of lenses 15 and 15c.

An additional measuring device may also utilise the rejected light from the polariser 14. This rejected light may be imaged by lens 15d onto a measuring device 16d. Here plane 16d is an image plane that is substantially equivalent to plane 16. Again, there may be magnification differences dependent on the focal lengths of lenses 15 and 15d.

The beam directors 47, 47', 47" may or may not be in place, depending on whether their use is required. The beam directors may each be one of either a beam splitter or mirror.

The image formed on planes 16, 16a, 16b, 16c, 16d may be aberrated if the light has been reflected or transmitted by a beamsplitter component in the various locations 47, 47', 47". This is likely to be of most concern for a beam splitter located at 47 for the reason that the light is being focussed through this component. Small changes in design may overcome such aberrations.

This embodiment has insufficient space to locate beam directors 47' and 47". Small changes in the optical layout and component details will be required to incorporate either or both of these beam directors.

A full field image of the sample may be obtained by locating an imaging CCD or camera at an image plane that may be one of planes 16, 16b, 16c,16d. It may be preferable to provide improved or alternative illumination of the sample. This is because the illumination optics are designed to focus the incident light to a point focus or narrow line focus as required for spectral analysis, whereas full field imaging requires a more uniform distribution of light over the full imaged field. This could be achieved by, for example, defocusing the illumination optics 2, or using an independent light source not shown.

For liquid or gaseous samples 6, the illumination light 1 and scattered light 8 may be transmitted through a transparent optical window 20 made of fused silica, although other materials may be used provided that they are transparent over the wavelength range of operation. Tilting the liquid sample holder about an axis substantially parallel to 17 causes the illumination beam reflected from the sample window and the collection beam to translate across the spectrometer slit 16. Light reflected from the sample window is translated at a greater rate than the collection beam. This is because the collection beam is refracted through the sample window 20, whereas the illumination beam is reflected. The difference although small, may be large compared to the width of the slit 16. The effect of this is that ghost images reflected from the sample window 20 are blocked by the spectrometer slit 16. The amount of tilt required for the suppression of back reflected light is reduced, so that the off axis aberrations induced by refraction through the sample window in the collection beam are minimised. For measurements on a solid sample, the transparent optical window 20 is not required, unless it is necessary to protect the sample from the environment, for example if it is hygroscopic.

It is desirable to make the design more rugged and user friendly by minimising the amount of movement required in any part of the interface. It is preferable for any required movement to be in the illumination optics, rather than the catadioptric collector optics because the illuminating wavelength is narrowband and known

whereas the collected light may contain a wide range of wavelengths. In the example, movement is required within the illumination optics 2 in order to maintain efficient focussing over all wavelengths. Without movement, it is still possible to obtain an output, but the aberration is worse unless a complex lens design is used. The lens and mirror components within the collection optics 9 remain static over the entire waveband of operation. Some movement may be required by the polarising prism 14.

The polarising prism 14 is required to operate over the entire waveband range of interest. The example described here has been optimised for operation over a range from 200-700nm. However, the system can operate at shorter and longer wavelengths too, for example the system may be operated using illumination from a ArF eximer laser. This type of illumination is useful in some spectroscopic applications and has a wavelength of 193nm. Operation over the entire waveband range in this example is achieved using an α-barium borate Glan Taylor prism which is orientated so as to transmit light that has a polarisation vector normal to the base plane 18. The polariser is rotated 21 about an axis of rotation 22; the axis of rotation 22 lies in or parallel to the base plane 18 and is suitably perpendicular to the optical axis 17. The polariser is rotated between +/-1° over the waveband 200nm - 700nm. The optical polarisation vector of the light entering the spectrometer slit 16 lies perpendicular to the long axis of the slit.

It is possible to change the polariser design or orientation within the catadioptric collection optics 9 so as to alter the polarisation vector of the light entering the spectrometer slit 16. For example, exchanging the Glan Taylor polariser with a Glan Thompson polariser may cause the optical polarisation vector at the plane 16 to become aligned along the long axis of the slit. It is likely that a Glan Thompson polariser would not be suitable for operation in the far ultra-violet end of the range near to 200nm. Alternatively the Glan Taylor polariser may be rotated about the optical axis 17. A 90° rotation will result in the optical polarisation vector for light incident at the spectrometer slit 16 being aligned along the long axis of the slit. In this case, the rotation axis 22 is orientated perpendicular to the base plane 18.

Rotation of the polariser may be avoided by using a selection of polarisers which are selectively inserted into the instrument. In this case, a polariser made of calcite may, for example, be used for the near ultraviolet, visible and infrared wavelengths. Another design of polariser is a Rochon design.

The optical throughput of the collection optics would be higher if the polariser was omitted because there are reflection losses at each surface and internal losses

in the polariser. If the polariser is removed, it could be replaced with a compensator in order to maintain efficient collection over the full field of view and to prevent a significant increase in aberrations such as lateral colour which for example would cause a change in magnification with wavelength. The role of compensator may be fulfilled by for example a fused silica block with the same outer dimensions as the polariser. If no compensator is used, then there may be some requirement to modify other components to improve performance.

In this embodiment, the illumination optics are designed to focus a 5mm Gaussian beam into a nominal F/6 cone of light into the sample. A line or point focus is generated depending on whether the illumination optical elements are spherical or cylindrical. The collection optics has a nominal F/2 collection angle and couples the light into F/7.5 at the slit plane 16. This results in a magnification ratio of 3.75 between the sample plane and slit plane. The magnification varies by 0.8% over the full operational wavelength range. The collection field of view exceeds 1.8mm. When compared with the system described in US5717518, the present invention has a collection f-number of 2. This means that image magnification is reduced by a factor 4, sampled area is increased by a factor of 16 and the complexity of the optics is considerably less.

Fig.3 is a side view of an example of the illumination optics 2. The illumination optics comprise a diverging lens 23 and a pair of converging lenses 24,25 separated by a distance, w 26. In use, the distance w is altered as the excitation wavelength changes in order to maintain focus at a fixed plane 7 within the sample 6. This adjustment is required in order to compensate for variations in the focal lengths of the lenses with wavelength. The sample is illuminated through an aperture in the turning mirror 4 and the separation w 26 of the diverging lens 23 and converging lens pair 24,25 is altered in accordance with the data set out in Table 1 and presented graphically in Fig. 4. The values given in the table were calculated using geometrical optics. The aperture of the illumination optics is F/7.1 at 220nm, F/6.4 at 400nm and F6.1 at 700nm. The aperture in the mirror 4 is adequate to clear the F/6.1 illumination beam.

A detailed description of the separation and curvature of the lenses and mirrors in the illumination and collection optics is given in tables 2 and 3. All distances are given in millimetres. The 45° turning mirror is labelled as surface S7 in table 2 and surface S4 in table 3.

The illumination optics lens surfaces will reflect a small proportion of light back towards the laser. The illumination optics are designed such that no components are

located at a back focus of the reflected light thereby minimising the likelihood of optical damage occurring to any of the optical components.

Wavelength in nm	lens separation, w in millimetres
220	27.3
250	31.1
300	35.4
350	38.2
400	40.1
450	41.4
500	42.4
550	43.2
600	43.8
650	44.3
700	44.7

Table 1

Surface, S	**radius of curvature**	**Axial separation**	**Material**
1	Plane		
		5.0	fused silica
2	+18.34		
		Adjustable, w refer to table 1	air
3	Plane		
		4.51	fused silica
4	-34.94		
		1.0	air
5	+34.94		
		4.51	fused silica
6	Plane		
		28.37	air
7	Plane		
		35.082	air
8	Plane		
		1.0	fused silica
9	Plane		
		0.5	water
10	Plane		

Table 2: detailed description of illumination optics

Surface	radius of curvature	Axial separation	material
1	Plane		
		0.5	water
2	Plane		
		1.0	fused silica
3	Plane		
		35.082	air
4	Plane		
		228.8	air
5	-190.78		
		-110.0	air
6	-94.85		
		50.36	air
7	+42.47		
		4.96	calcium fluoride
8	+58.49		
		54.68	air
9	-87.6		
		2.95	fused silica
10	+30.36		
		20.36	air
11	Plane		
		20.40	α-barium borate
12	Plane		
		10.00	air
13	+123.6		
		4.3	calcium fluoride
14	-55.38		
		85.16	air
15	Plane		

Table 3: detailed description of collection optics

The illumination optics design preferably has all its lenses located prior to the turning mirror 4. This is a so-called long working distance focussing system. A prism could be used in place of the mirror 4, but the results tend to be less good. The design in Fig. 3 achieves the necessary working distance by expanding the illumination beam diameter with the lens pair 23,24 prior to focusing the light into the sample using lens 25. The amount by which the beam needs to be expanded depends on the characteristics of the incident light 1, which in turn dictates the choice of design of the illumination optics 2. The illumination optics 2 may comprise

cylindrical optics if line illumination is required on or within the sample. Spherical optics are used for point illumination.

Fig. 5 shows four different arrangements of the illumination optics 2 which may be used. For the example of Fig 5a, the sample is illuminated through an aperture 3 in the turning mirror 4; whereas for the example of Fig 5b, the sample 6 is illuminated by a small reflecting turning mirror 27. Cylindrical or spherical focussing lenses are used to form either a line or point focus on or in the sample. Out of the two arrangements, that of Fig. 5a is preferred because of the risk of optical damage caused by the illumination light, occurring to the turning mirror 27 or possible alterations of the polarisation state being imposed. This problem is particularly acute in the far ultraviolet where availability of suitable mirror coatings is limited.

In Fig.5c, illumination is from the side in a so-called 90° scattering geometry. Spherical lenses are used, so as to form a point focus. The collection optics images light that is scattered from along the length of this focussed region.

In Fig. 5d, illumination is illustrated in a transmission type geometry. Cylindrical or spherical lenses may be used to form either a line or a point focus on or in the sample.

To ensure efficient operation, the orientation of the illumination focus should coincide with the image 7 of the spectrometer slit 16.

It is also conceivable to use a collimated illuminating beam, which has no focussing components. This approach is least preferred on account of the poor coupling of light into the slit 16 of the measuring device.

It is preferable that any pump light 1 being directly scattered or reflected into the collection optics 9 and the plane 16 is avoided. To avoid the turning mirror 4 causing such an occurrence, the aperture 3 is shaded from the main collection optical path by the shadow caused by the convex secondary mirror 11. The collection and illumination optical paths therefore only intersect a common volume in space around the sample 6, 20.

The operation of the polariser is angle dependent. The α-barium borate prism incorporated within the particular example being described here transmits linearly polarised light with a polarisation vector that is orthogonal to the long axis of the slit 16, although this invention is not limited to this type of polariser or this performance. The collection optics is designed so that the light is substantially collimated as it passes through the prism. Within the design example, the variation of ray angles is less than +/-2.4° for rays orientated parallel to the base plane 18 and practically zero for rays in a plane orthogonal to the base plane 18.

The α-barium borate polariser needs to be rotated by +/-1° in order to achieve the full waveband coverage. This rotation causes the projection of the F/7.5 numerical aperture of the slit 16 to track over the primary 10 and secondary 11 mirrors. The secondary mirror 11 has to be made sufficiently large in order to shadow the turning mirror aperture 3.This is in order to prevent the possibility of direct scattering of illumination light from the aperture 3 into the measurement device slit 16. The necessary size of the secondary mirror 11 is thus affected by the rotation of the prism 14. The secondary mirror diameter is increased if the polariser needs to be rotated through a larger range of angles, resulting in a larger obscuration. For a +/-1° rotation of the polariser, the obscuration is 25%. This increases to 28% for a polariser rotation range of +/-2°.

For the purposes of this application, transverse ray aberrations are defined with reference to Fig. 6. This shows an entrance pupil plane 28, and an image plane 29. The co-ordinates of points on these planes are described by orthogonal axes: the x, ξ or sagittal axes; and the y, η or meridional axes. An unaberrated ray intercepts the entrance pupil plane 28 at P and the image plane 29 at Q whereas an aberrated ray intercepts the image plane 29 at R. Point R is displaced from point Q a distance of $d\xi$ along the ξ-axis and a distance $d\eta$ along the η-axis. Distance $d\eta$ is the meridional aberration and distance $d\xi$ is the sagittal aberration. P is at co-ordinate (x_1,y_1) in the entrance pupil plane 28. The meridional aberration plot is the meridional aberration $d\eta$ plotted versus the y co-ordinate of P; the sagittal aberration plot is the sagittal aberration $d\xi$ plotted versus the x co-ordinate of P.

For the purposes of this application, paraxial chromatic aberration is defined with reference to Fig. 7. This shows rays propagating from an exit pupil 30 to an image plane 31. Paraxial rays with wavelength λ_R form an image at R and paraxial rays with wavelength λ_S form an image at S. The paraxial chromatic shift is defined as the movement of the focus with wavelength along a direction that is parallel to the optical axis, depicted as dl in the Fig. 7.

For the purposes of this application, wavefront aberration is defined with reference to Fig. 8. This shows an unaberrated spherical wavefront 32 at the exit pupil 30 illuminating an image point T. The figure also shows the aberrated wavefront 33 at the exit pupil. The wavefront aberration is defined as the deviation of the aberrated wavefront from the unaberrated wavefront.

It is standard practice to characterise the performance of an optical system in terms of a point spread function. This invention introduces the concept of a line spread function in order to describe system performance when imaging a line image.

The line spread function is defined as the point spread function along a line that runs perpendicular to the line image. This is illustrated in Fig. 9 which shows an object plane 34 with orthogonal axes x and y; and an image plane 35 with orthogonal axes ξ and η; axes x and ξ are parallel; axes y and η are parallel. The line illumination runs along the y-axis as indicated. The line spread function from an impulse at co-ordinate $(0,y_1)$ on the object plane is generated along the line $\eta=\eta_1$on the image plane 35. An example line spread function is shown in the insert 36 of Fig 9.

The imaging performance of the collection optics is defined in terms of a line-spread function owing to the use of a line focus illumination. For the purposes of this definition, the slit plane 16 is taken to be within the object plane 34 in Fig. 9, such that the long axis of the slit runs along the y-axis. The sample plane 7 is taken to be the image plane 35. The line-spread function is then the intensity at the sample plane 7 generated by an impulse at the slit plane 16. The centre of the slit is at co-ordinate (0,0) on the object plane 34 in Fig. 9, and the slit extends from $y=-y_f$ to $y=y_f$. The full slit height is at $y=y_f$.

Apochromatic performance in the collection optics is achieved by designing the lenses 12,13 to accept a real image from the spherical mirrors 10, 11, so that most of the optical power is concentrated in the mirrors. The chromatic aberrations in the lenses are balanced by varying the conjugate projected from the spherical mirrors. It is possible to get reasonable chromatic aberration compensation with only fused silica lenses, although in the example of the design described here a 3-lens combination of calcium fluoride and fused silica has been selected. The projection of a real image of the illuminated region by the collection means into the input means facilitates high levels of chromatic correction to be achieved using lenses that substantially avoid the normal crown-flint geometry, whereby a converging lens of low dispersion would be compensated by a diverging lens of high dispersion, for colour compensation; and therefore means that the primary chromatic aberration is compensated with minimum lens powers, such that secondary spectrum is very much reduced.

Fig. 10 illustrates the line-spread function at wavelengths of 220nm, 400nm and 700nm for an impulse at the centre of the slit 16 and full slit height. Referring to Fig.9, the centre of the slit is at y=0 in plane 34; and the full slit height is at $y=y_f=3.5$mm in plane 34. The design assumes a liquid sample 6 with refractive index 1.33 behind a 1mm fused silica window 20; the line spread function is calculated along a plane 7 that is 0.5mm into the liquid. The performance curves are generated using full diffraction calculations.

The results shown in Fig.10 along with other line spread function plots not shown here indicate that the line spread function has a width less than 10μm for a focussing depth ranging between 0-1mm into the liquid sample, over the wavelength range 200-700nm.

There is a straightforward scaling relation between the line spread function at the sample plane generated by an impulse at the slit plane, and the reverse situation of the line spread function at the slit plane generated by an impulse at the sample plane. For the embodiment being described, the scaling is nominally 3.75. The width of the line spread function at the slit plane 16 is thus within 37.5μm for a focusing depth between 0 -1mm into the sample 6.

A comparison between the line-spread function of the collection optics and a region typically illuminated by an incident laser beam is shown in Fig.11. The incident illumination 1 is assumed to have a Gaussian profile with a 5mm diameter at the 1/e squared intensity level, and a divergence of 1 mrad. Fig. 11a shows the comparison at the centre of the slit (on axis); Fig. 11b shows the comparison at the full slit height. The illumination at wavelengths 220, 400 and 700nm overlay and are indicated as 37 on the Fig.11. The line spread functions at 200,400 and 700nm are labelled as 38,39,40 on the figures. In certain situations it is preferable to confine the illumination beam to a smaller focussed region, for example, when high spectral or spatial resolution measurements are required and there is insufficient laser power in the sampled region to ensure an adequate measured signal level. The illumination beam may be better confined by, for example, reducing the divergence of the illumination beam. The system can also operate at extended depths, e.g., 10mm or 15mm into the sample under test, and modelled performance results at such depths have been derived at 700nm.

Transverse ray aberrations for various collection optic embodiments are shown in Fig. 12. Fig. 12(a) illustrates transverse aberrations for a collection optic embodiment based upon a two fused silica lens and two mirror catadioptric design The meridional axis is aligned along the long axis of the slit 16, with the sagittal axis aligned across the slit. The meridional and sagittal aberrations are presented for an impulse located on axis at the slit 16, at 2.45mm (70% slit height) and 3.5mm (full slit height). Fig 12(b) illustrates transverse ray aberrations for an alternative collection optic embodiment based upon a three lens/2mirror catadioptric design, using two calcium fluoride and one fused silica lens. Fig 12(c) illustrates transverse ray aberrations for an alternative collection optic embodiment based upon a four

lens/2mirror catadioptric design, using two calcium fluoride and two fused silica lenses.

Transverse aberrations for the collection embodiment detailed in table 1 are shown in Fig. 12(b). The meridional plots indicate that there is a variation of 0.8% in magnification within the collection optics across the full waveband. This has been confirmed in optical analysis not presented here.

The paraxial chromatic focal shift at the sample plane is shown in Fig. 13. This indicates an axial shift in the paraxial focus of less than 20μm over the full wavelength range 200-700nm. This is in agreement with full diffraction analysis not presented here.

The collection optics wavefront plots are shown in Fig.14. The maximum (peak to valley) and RMS wavefront errors are tabulated in Table 4. The design performance can be seen to have a maximum wavefront error of 1.8 optical wavelengths.

location of impulse		λ_1=220nm	λ_2=400nm	λ_3=700nm
slit centre	peak to valley:	$0.5 \times \lambda_1$	$0.9 \times \lambda_2$	$0.2 \times \lambda_3$
	RMS value:	$0.1 \times \lambda_1$	$0.3 \times \lambda_2$	$0.05 \times \lambda_3$
full slit height	peak to valley:	$1.8 \times \lambda_1$	$1.0 \times \lambda_2$	$0.7 \times \lambda_3$
	RMS value:	$0.3 \times \lambda_1$	$0.2 \times \lambda_2$	$0.1 \times \lambda_3$

Table 4: wavefront errors read from Fig. 13

Rotation 21 of the polarising prism around the axis 22 causes a change in the transverse aberrations of the collection optics. Fig.15 shows transverse aberration plots for 0°, 1° and 2° of rotation. The main effect is an increase in the sagittal aberrations, causing the line image at the sample to translate in a direction normal to the base plane 18 by 4μm at 1° tilt and 8μm at 1° tilt over the wavelength range 220nm to 700nm. This change in aberration is due to chromatic dispersion in the prism and is a first order effect that cannot easily be removed.

Projection of substantially collimated light through the prism minimises the likelihood of aberrations arising due to skew rays. The polariser material is birefringent resulting in a non-linear change in the refraction angle with propagation

direction within the polariser. The use of uncollimated light may lead to an increase in the level of aberrations due to such effects.

Projection of non-collimated light through a tilted prism will induce non-rotationally symmetrical aberrations into the wavefront, which may also be undesirable, since these can be difficult to correct.

Transverse ray aberration plots for a collection optic design using 2, 3 and 4 lenses are shown in Fig. 12(a-c). These show that aberrations are generally well corrected over the full waveband, except for a change in magnification. Aberrations cause the magnification of the collection optics to vary with wavelength. This effect is 0.8% with a 3 lens design and practically zero with a 4 lens design.

The inclusion of more lenses within the collection optics enables better aberration compensation as well as a possible reduction in the central obscuration in the collection optics. The obscuration for the 3-lens design is calculated to be 25% and is expected to drop to around 20% for a 4-lens design. However this improvement must be offset against increased optical losses that may arise with the inclusion of an extra optical component. Reduced aberrations also leads to an improvement in the spatial resolution as well as a less aberrated wavefront being projected into the entrance of a measuring device located at plane 16. The wavefront aberrations may have a deleterious effect on the image quality formed within the measuring device.

For optical spectroscopy, the measuring device is some type of spectrometer. The effect of aberrations may be to limit the measurement performance, for example spectral resolution of the measurement; or the capability to discriminate a weak signal in the presence of a strong signal. By means of an example, Raman spectroscopy regularly requires the capability to discriminate a weak signal in the presence of a strong signal; the weak signal and strong signal have a small wavelength difference, typically of the order of 1-20 nanometers. A spectrometer operates by spatially separating the wavelengths at the exit plane of the spectrometer. A spectrometer acts as an imaging system, by which the entrance slit to the spectrometer is imaged onto a detector plane or exit slit . This imaging action results in a finite image of the entrance slit forming at the detector plane or exit slit of the spectrometer. The spread of this light is governed by the point spread function of the spectrometer.

The effect of an aberrated wavefront entering the spectrometer is likely to cause further spreading of the light at the detector plane or exit slit of the spectrometer. This kind of spreading can have a detrimental effect on spectrometer

performance. The problem may be particularly acute if the spectrometer is required to separate light comprising two or more spectral components that are closely separated in wavelength; and where the spectral components have hugely different relative intensities. This is the situation frequently encountered in Raman spectroscopy, to name a single example application.

In conventional Raman spectroscopy the requirement is to separate a high intensity Rayleigh scattered radiation from a low intensity signal called the Raman excitation. The Rayleigh radiation is usually narrow band or monochromatic in wavelength. The Raman excitation comprises one or more wavelengths that is usually narrowband and usually within 1 to 5000 cm^{-1} or wavenumbers from the Rayleigh excitation. The potential problem caused by Rayleigh light being mixed into the detected Raman scattered radiation is illustrated with reference to Fig. 16. This shows the intensity distribution of the Rayleigh 42 (excitation) and Raman 41 light across the image plane within a spectrometer measuring instrument that results from an impulse at the sample. The Raman peak intensity is typically many (for example 7) orders less than the Rayleigh light.

Both the Raman and the Rayleigh peaks exhibit side lobes. The insert 43 of Fig. 16 shows in more detail the spatial overlap of Rayleigh side lobes 44 and the Raman signal 41. This example illustrates that the detection limit for the Raman signal may be limited by the intensity of side lobes of the Rayleigh radiation.

Consideration of side lobe levels may be important when investigating weak Raman lines that are close to the Rayleigh line. Calculations have been performed to estimate the effect on spectrometer performance caused by an aberrated wavefront entering the entrance slit of a spectrometer. The calculations considered various aberration types that include defocus and coma wavefront aberration; for purposes of the analysis, these aberrations were imposed on a plane wavefront at the pupil plane of the spectrometer. The calculations estimated the intensity of the Rayleigh side lobes that coincide with a Raman excitation that were shifted by 100 wavenumbers from the Rayleigh radiation. These calculations were based on diffraction analysis; the calculations assume a central wavelength of 200nm, a single grating spectrometer with an entrance aperture of F/7.5, a 2400lines/mm grating and 640mm focussing mirror. The spectrometer is assumed to image the entrance aperture which is coincident with plane 16 onto a detector plane. Table 5 tabulates the estimated intensities of the Rayleigh side lobe for various amounts of wavefront aberration. The intensities are normalised to unit intensity for the central maximum of the Rayleigh peak (on axis).

Wavefront aberration	Rayleigh side lobe level at 100 cm^{-1} from the central peak
2 waves of coma	$<5x10^{-6}$
25 waves of defocus	$<7x10^{-4}$
35 waves of defocus	$<3.5x10^{-3}$
50 waves of defocus	<0.75

Table 5

The 3-lens design has a wavefront error design performance less than 2 wavelengths. The results presented in the table therefore indicate that, in the absence of any defocused light reaching the detector, the side lobe level caused by coma wavefront aberration is suppressed to an intensity level less than $5x10^{-6}$ relative to the Rayleigh peak.

It is conceivable that out of focus light may pass through the slit 16 and enter the spectrometer detector system. Ray trace modelling indicates that 30 waves of defocus in the collection optics will form an out of focus image of the illumination focus 7 that is 0.71mm at the entrance slit 16. It is expected that this can be considerably reduced if the slit to the spectrometer detector system 16 is set to a width less than 100μm.

There are a number of ways in which the mixing of the Rayleigh light with the Raman signal may be avoided. These methods may be used separately or in combination and include the following: use of an alternate collection embodiment with different aberration performance characteristics; use of a narrow entrance slit 16 to the spectrometer ; limitation of the height of the slit 16; use of optical components manufactured and assembled to a high tolerance; tilting of the sample in order to prevent out of focus light that has been scattered by any optical surface or window directly in front of the sample surface from entering the spectrometer slit; appropriate choice of secondary mirror diameter in order to prevent illumination light that may have been scattered by the hole in the 45° mirror from entering the spectrometer slit; prevention of direct coupling of illumination light into the collection optics and hence into the spectrometer slit by use of an obscuration plate appropriately positioned within the collection optics. These methods will now be described.

Aberrations arising in a particular embodiment are likely to have an adverse affect on performance by increasing the intensity in the side lobe of an image formed

at the image plane 16. Results shown in Fig. 12 indicate that there is likely improvement in performance by increasing the complexity of the embodiment.

The use of a narrow slit reduces out of focus light entering the spectrometer. Factors that dictate the narrowest slit that can usefully be employed include the width of the line spread function for the collection optics.

The use of a slit with a reduced height will reduce the wavefront aberration of the light entering the spectrometer.

The optics should be manufactured and assembled within tight tolerances to ensure that the optical design specification is achieved, thereby ensuring optimum wavefront quality for the light entering the spectrometer. Wavefront quality is key to ensuring the side lobe level of the Rayleigh light is suppressed.

Reflections from the sample window 20 will cause high side lobes unless vignetted by the entrance slit. The nominal focus is at a depth of 0.5mm into the sample fluid. In this case, reflections off the inner surface of the window 20 have been calculated to induce 60 waves of defocus. The wavefront transmitted through a 90μm slit at the entrance of the spectrometer has been estimated to be less than 8 waves, limiting sidelobe intensities to of the order of 10^{-2}.

Reflections from the liquid sample window 20 can be avoided by tilting the sample by over 15° so that reflections are imaged by the collection optics just outside the slit aperture 16. Tilt introduced into the sample window will induce astigmatism that can be corrected by refocusing the optics, on the basis that aberrations orientated along the direction of the slit 16 do not affect the system performance. However, astigmatism will set an upper bound for the size of a point focus formed by spherical illumination optics.

There is a possibility that illuminating light passing through the hole in the 45° mirror may be directly scattered via the collection optics into the spectrometer slit. This is avoided by a design feature within the collection optics whereby the secondary mirror 11 is used to shadow any such scattered light. The focussing mirrors10,11 in the collection optics form a central obscuration of the aperture, caused by the shadow of the smaller secondary mirror 11 being projected onto the spectrometer slit 16. The aperture 3 in the 45° mirror 4 is within the shadow projected by the secondary mirror 11.

There is a significant out of focus volume in the sample that is viewed by the collector optics and illuminated by the laser. This out of focus light may be blocked from entering the spectrometer slit by appropriate placement of a baffle within the collection optics. This problem may be particularly acute when the sample is a

volume scatterer. A suitable location is adjacent to the back surface of the secondary mirror 11.

In order to understand how the out of focus light is coupled in to the spectrometer, reference is made to Fig. 17. Fig.17, (a) shows the line focus of the illumination light. Fig. 17(b) shows the volume of light collected to a single point along the spectrometer slit. This is a hollow cone. Fig. 17(c) shows the coupling of the illumination light and the collection optics. In region 45 illumination light may be coupled into the collection optics and hence into the spectrometer. This coupling includes light both from within and outside the optical focus region. In region 46 no out of focus illumination light is able to couple into the collection optics.

The coupling of light from the out of focus region can be avoided using a rectangular obstruction as shown in Fig. 17(d) within the collection optics. Fig. 17(e) shows that the rectangular obstruction acting so as to block out of focus light directly coupling into the collection optics and spectrometer entrance slit. The rectangular obstruction thereby is able to shade the out of focus light at the expense of a greater obscuration which increases from ~25% to ~53% for the 3-lens design. The rectangular obscuration will reduce the volume of sample which the illumination may couple light into the collection optics to less than 0.2mm length.

The present invention provides an optical imaging system interface which efficiently focuses incident primary excitation light onto a sample as a line or point, collects secondary scattered light from the sample and injects it into an imaging system across a broad spectral wavelength range from deep ultraviolet to the infra red with the minimum possible user intervention. It is ideally suited for use in Raman spectroscopy, but can be used for more general spectroscopy applications. It may also be adapted for microscope sample imaging applications.

CLAIMS

1. A spectral analysis interface, the interface comprising illumination optics to focus light from a narrow band source onto a sample; collection means for collecting incident light scattered from the sample; and input means to input the collected light to a spectral analysis device; wherein the illumination optics focuses the light to a line or point focus; wherein the input means comprises refracting components; wherein the collection means comprises a primary reflector and a secondary reflector such that the arrangement of the primary and secondary reflectors gives rise to a central obscuration; wherein illumination of the sample is within the region obscured by the central obscuration; wherein the collection means projects a real image of the illuminated region of the sample to the input means; wherein the input means projects a real image of the illuminated region of the sample to the spectral analysis device; and whereby substantially full chromatic aberration correction is maintained at the spectral analysis device over a range of illumination wavelengths without the need to change the relative positions of any of the components of the collection means or input means.

2. A spectral analysis interface according to claim 1, wherein the range of illumination wavelengths is at least 200nm and includes within the range 250nm and 393nm.

3. A spectral analysis interface according to claim 1 or claim 2, wherein the range of illumination wavelengths is at least 500nm and includes within the range 250nm and 693nm.

4. A spectral analysis interface according to any preceding claim, wherein the illumination optics comprise either cylindrical or spherical focussing optics to produce line or point focus respectively.

5. A spectral analysis interface according to any preceding claim, wherein the incident light is from a monochromatic light source.

6. A spectral analysis interface according to any preceding claim, wherein the collecting means further comprises a turning mirror to reflect scattered light from the sample onto the primary reflector.

7. A spectral analysis interface according to claim 6, wherein the incident light is incident on the sample through an aperture in the turning mirror.

8. A spectral analysis interface according to claim 7, wherein the aperture in the turning mirror is so positioned so that stray light scattered by the aperture is prevented from reaching the spectral analysis device by the obscuration.

9. A spectral analysis interface according to any preceding claim, wherein the primary reflector comprises a reflecting concave mirror the secondary reflector comprises a reflecting convex mirror and the input means comprises at least one lens.

10. A spectral analysis interface according to any preceding claim, further comprising an analysing element.

11. A spectral analysis interface according to claim 10, wherein the analysing element comprises one of a polariser, compensating block, prism or wavelength filter.

12. A spectral analysis interface according to claim 11, wherein the polariser comprises one of α - barium borate quartz, and magnesium fluoride.

13. A spectral analysis interface according to any preceding claim, further comprising a baffle such that substantially only light from close to the focus is input to the analysis device.

Fig.1.

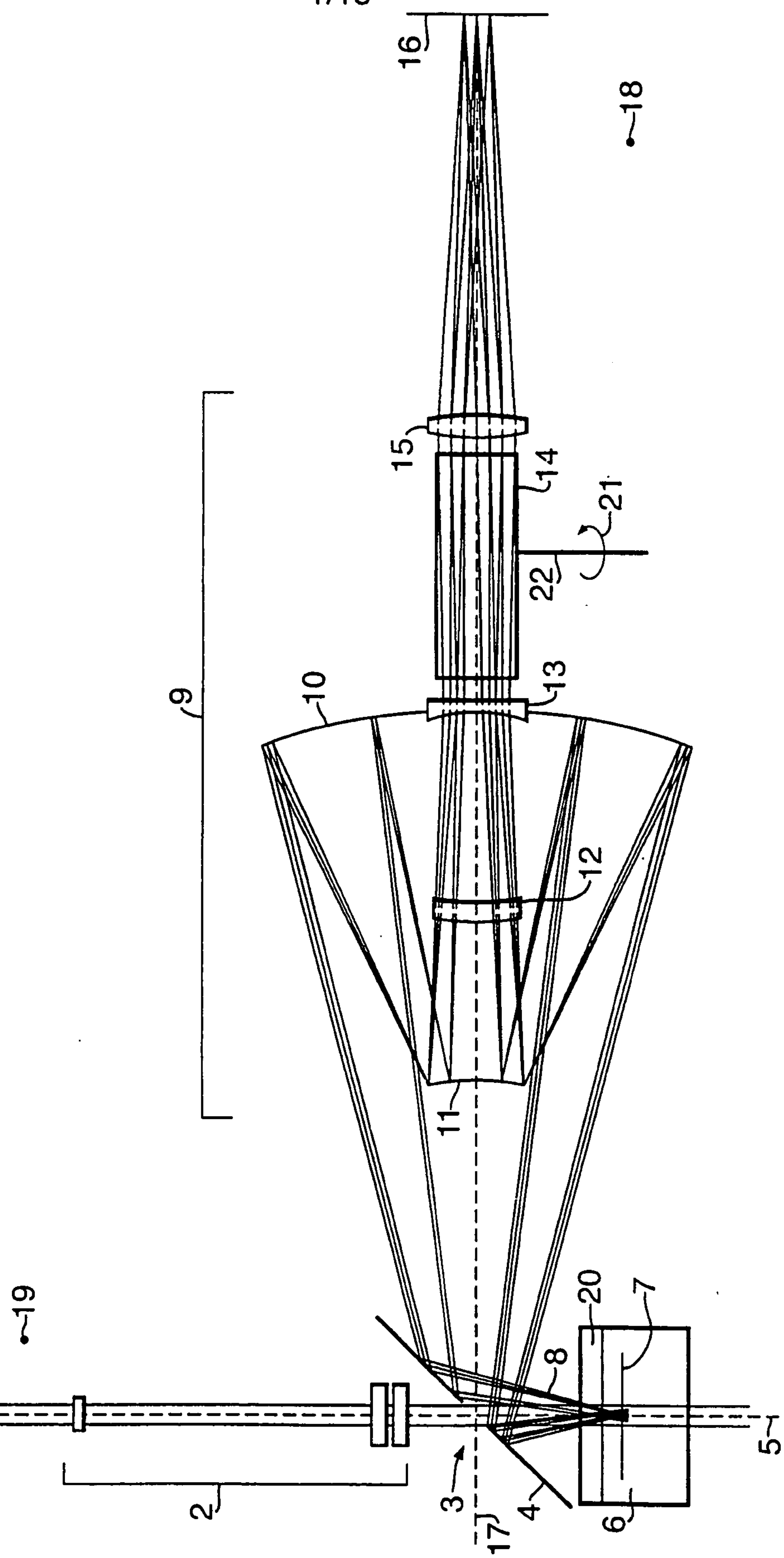


Fig.2.

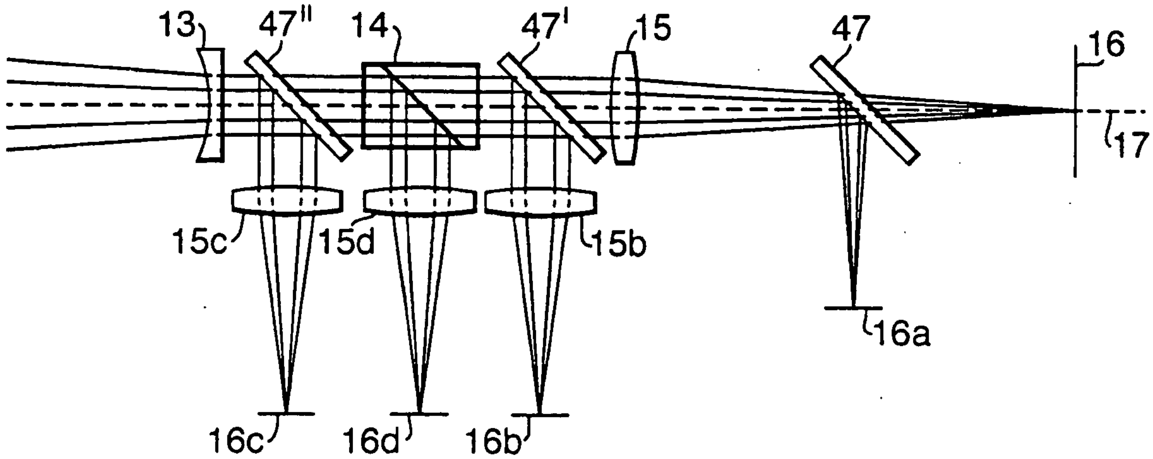

13
47''
14
47'
15
47
16
17
15c
15d
15b
16a
16c
16d
16b

Fig.3.

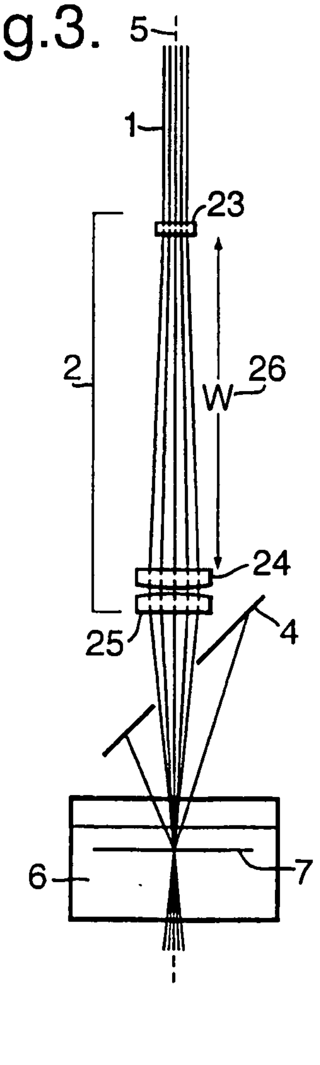
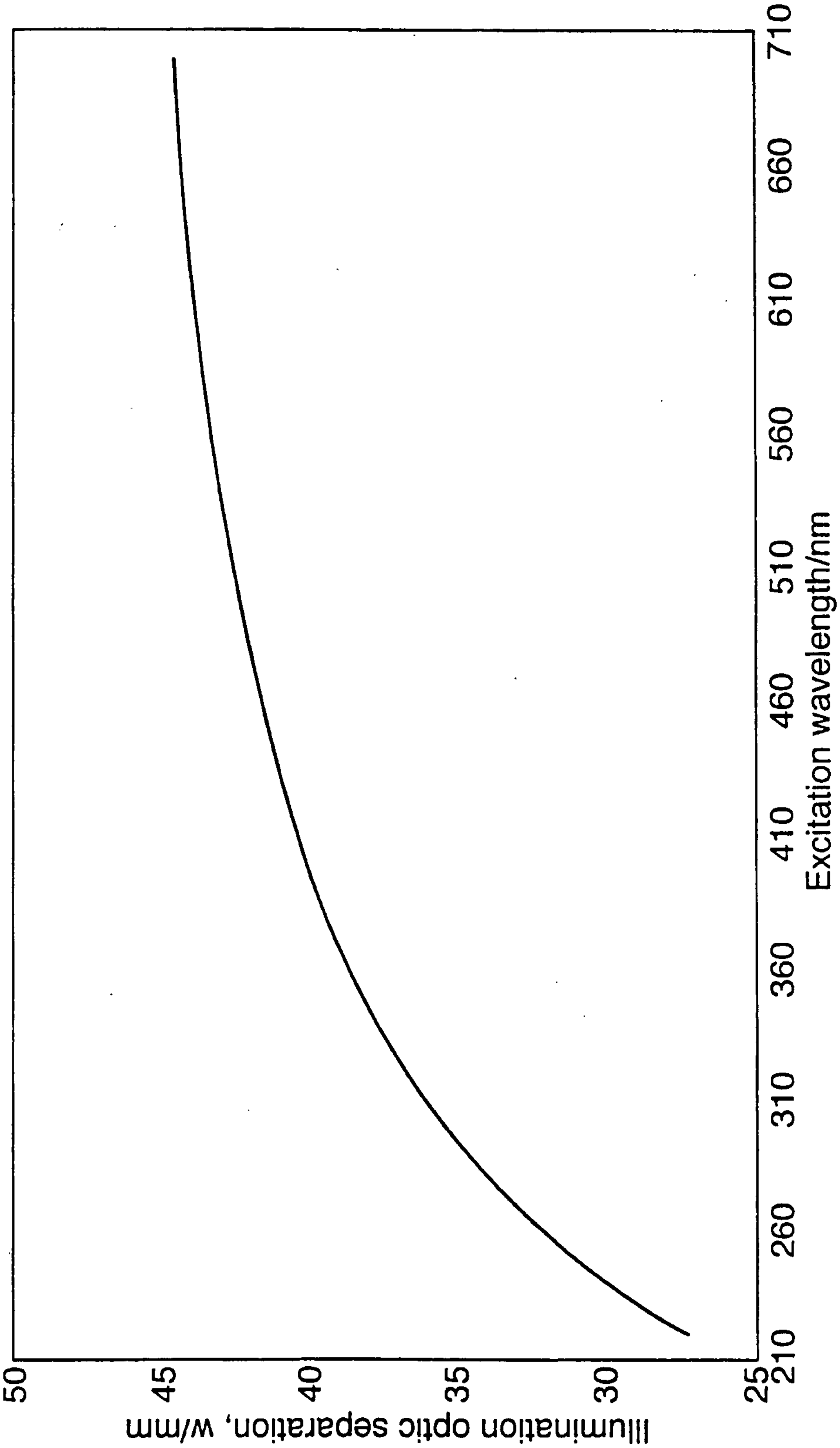

5
1
23
2
W
26
24
25
4
6
7

Fig.4.


50
45
40
35
30
25
Illumination optic separation, w/mm
210
260
310
360
410
460
510
560
610
660
710
Excitation wavelength/nm

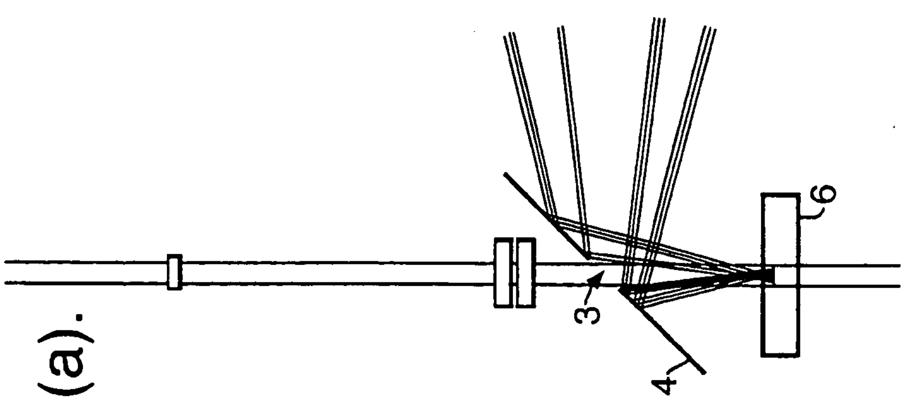


Fig.5(a).

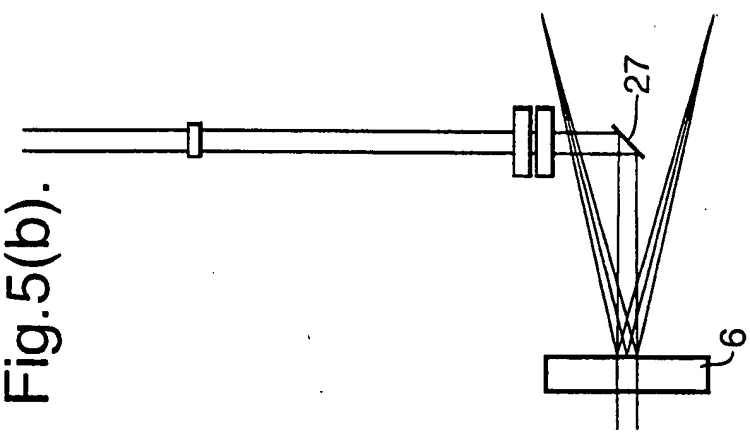


Fig.5(b).

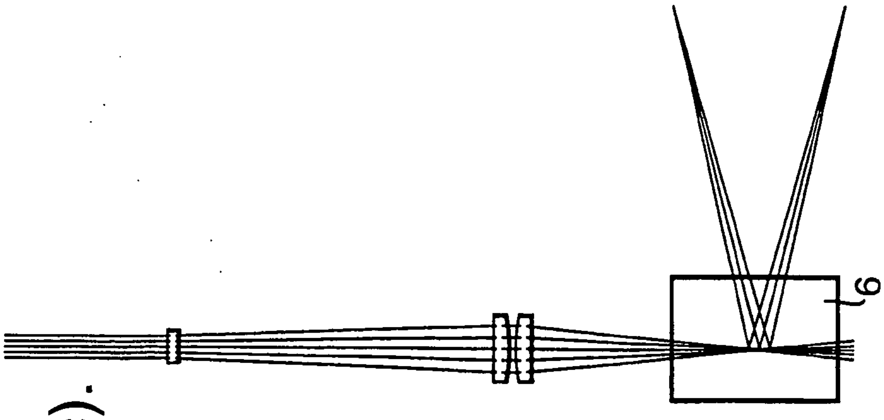


Fig.5(c).

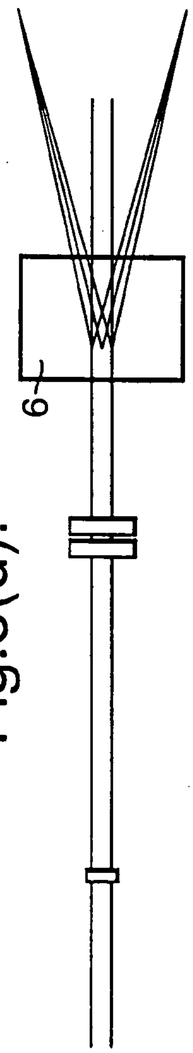


Fig.5(d).

Fig.6.

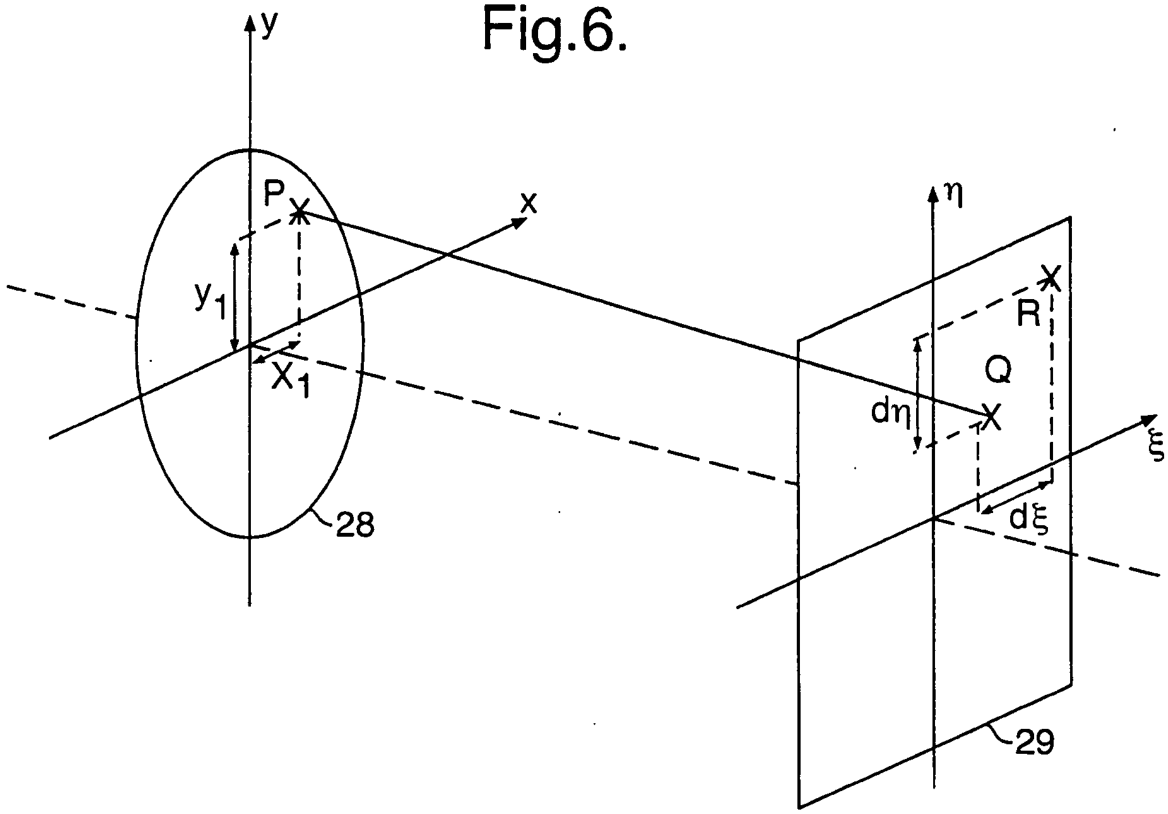


Fig.7.

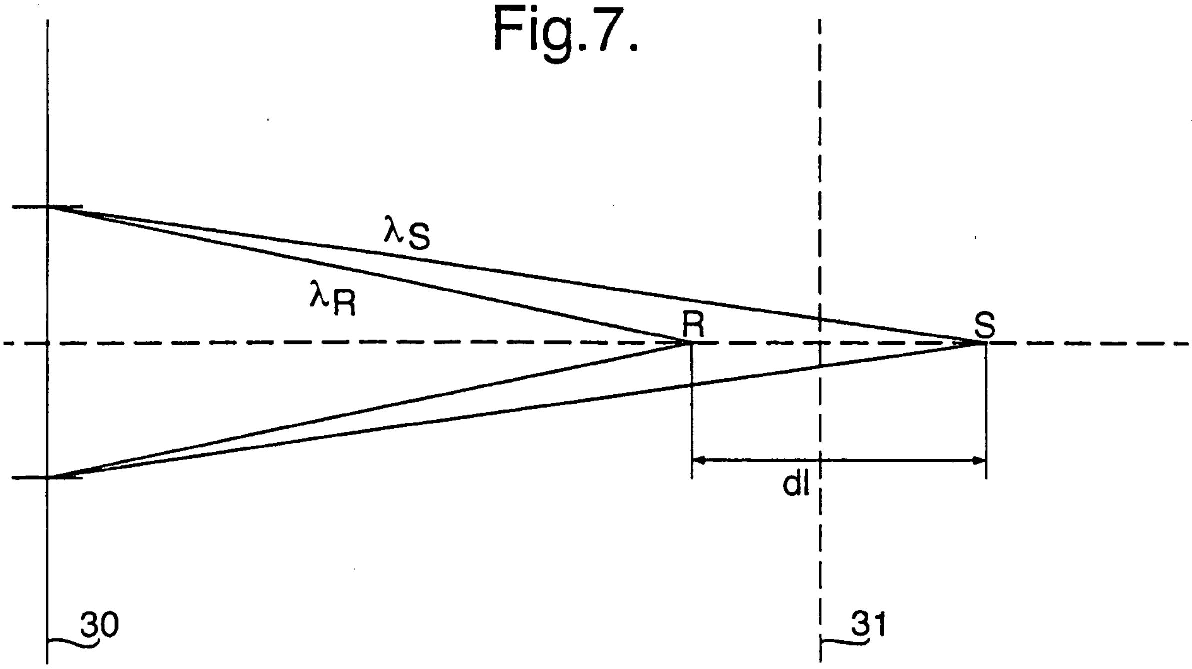


Fig.8.

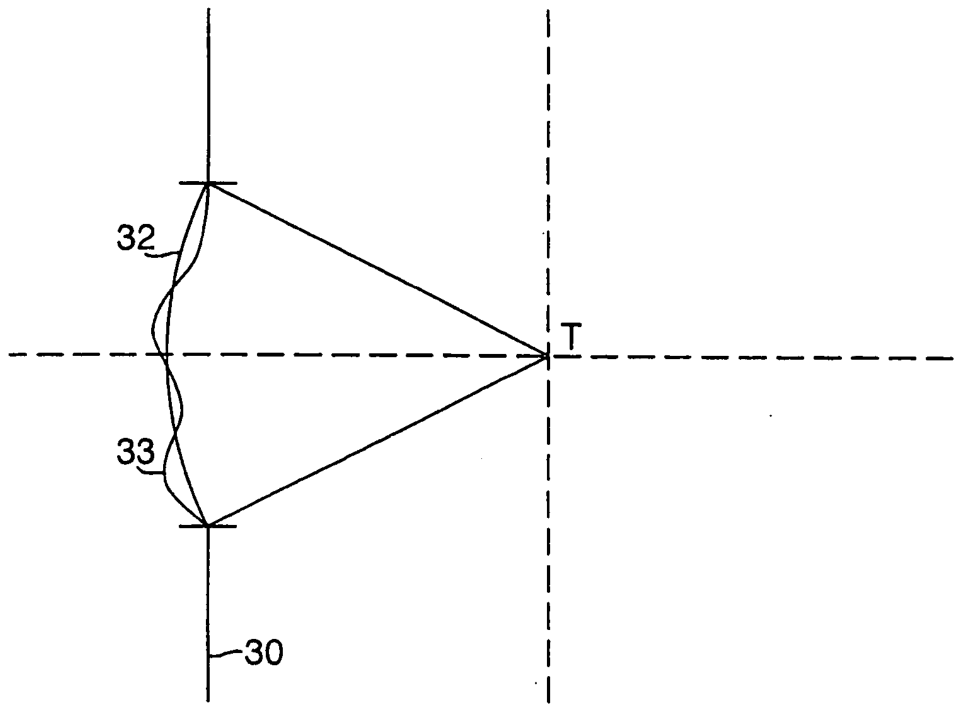


Fig.9.

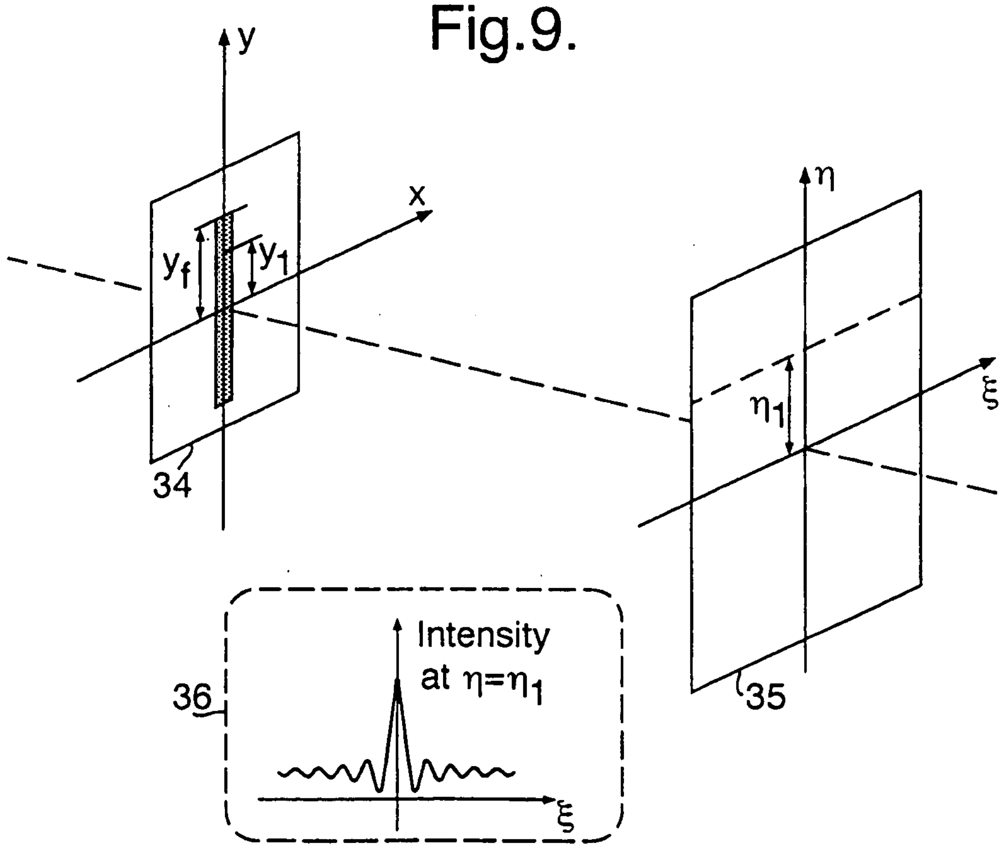
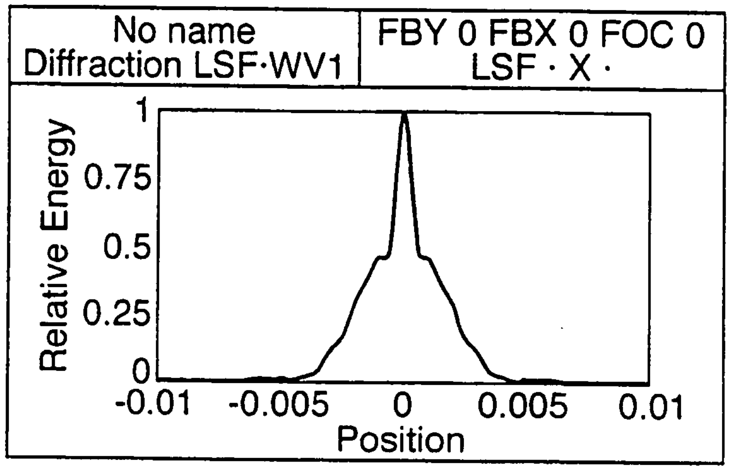


Fig.10(a).

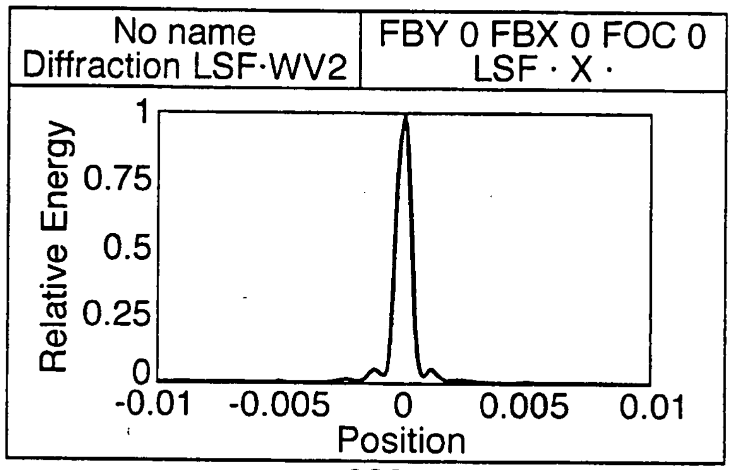
Slit Centre



400nm

Fig.10(b).

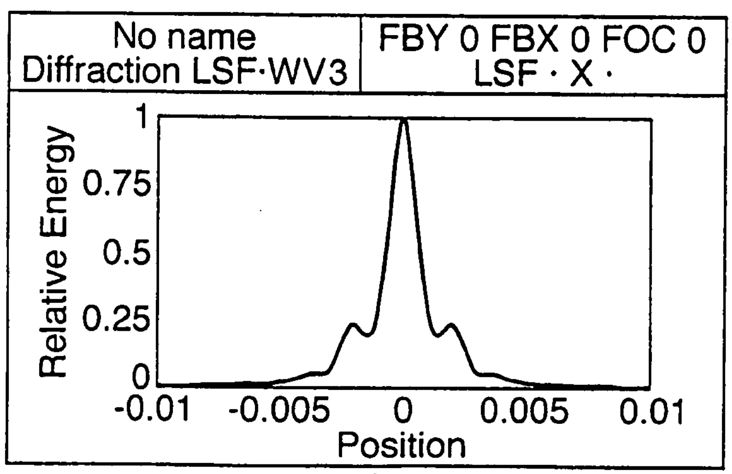
Slit Centre



220nm

Fig.10(c).

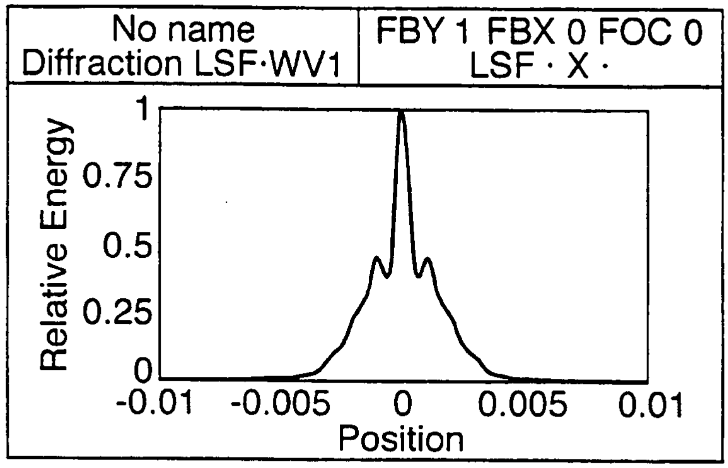
Slit Centre



700nm

Fig.10(d).

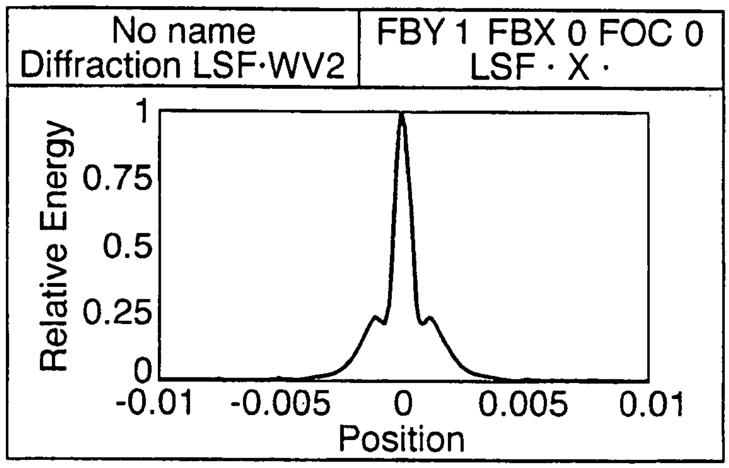
Full Slit Height



400nm

Fig.10(e).

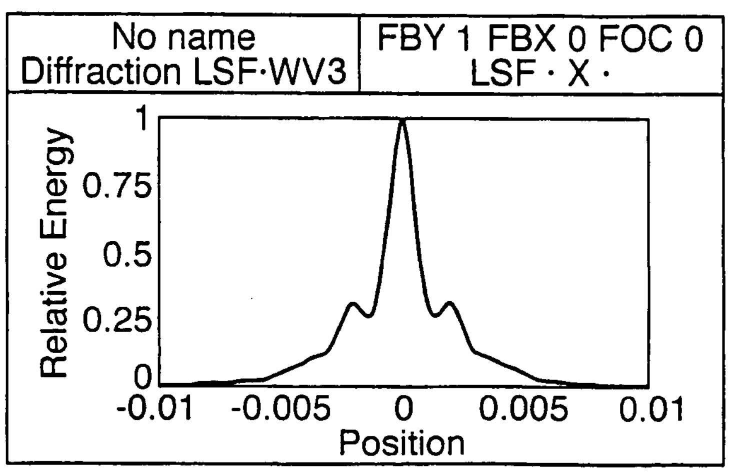
Full Slit Height



220nm

Fig.10(f).

Full Slit Height



700nm

Fig.11(a).

Centre of Slit:

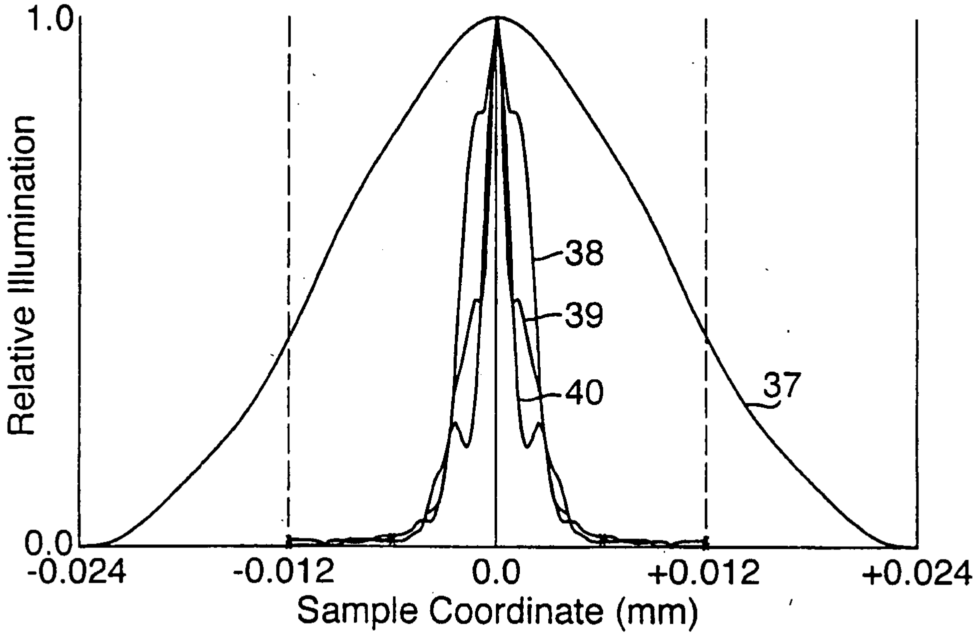


Fig.11(b).

Full Height of Slit:

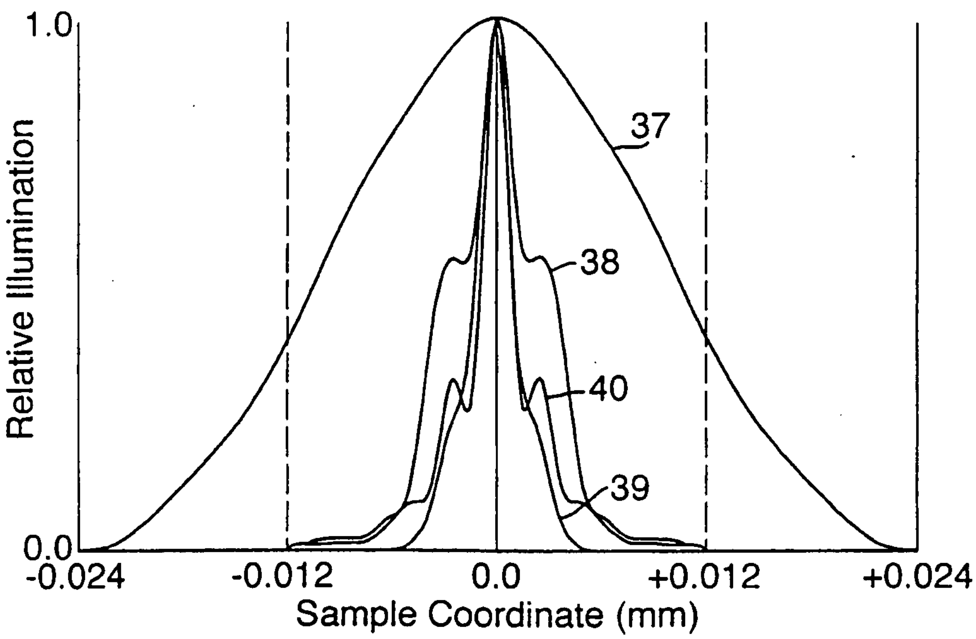


Fig.12(b).

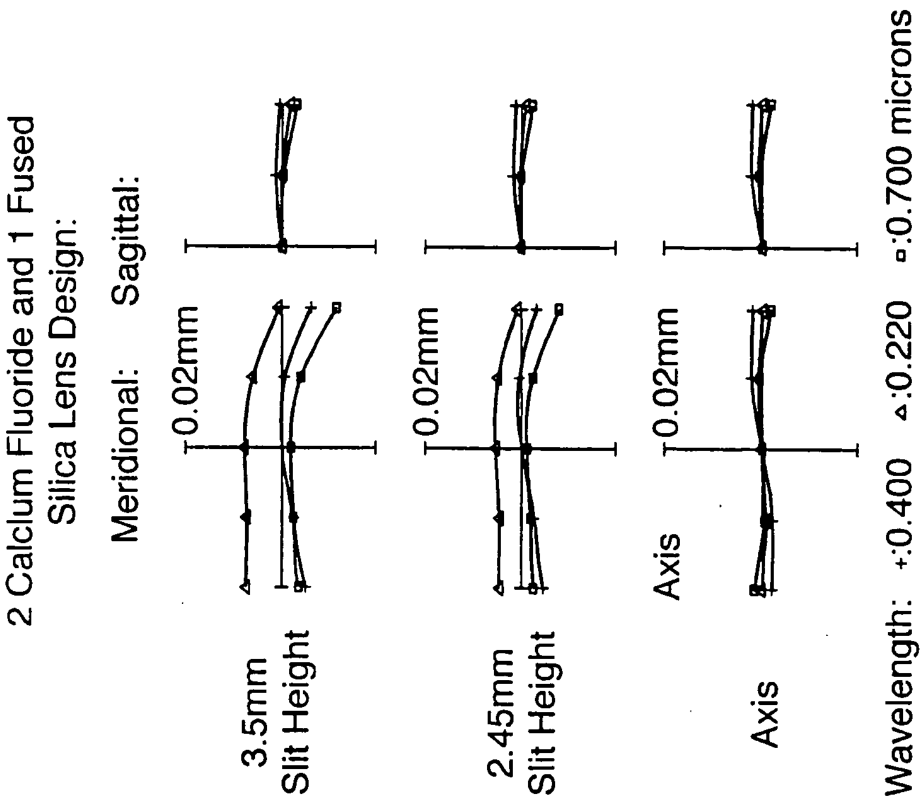


Fig.12(a).

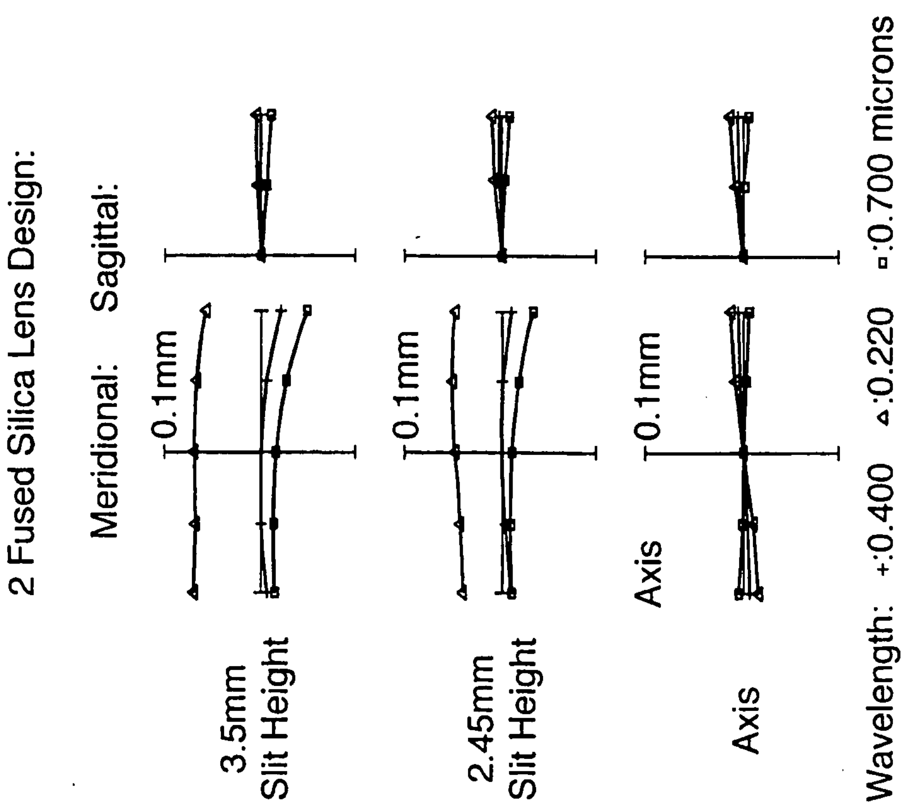


Fig.12(c).

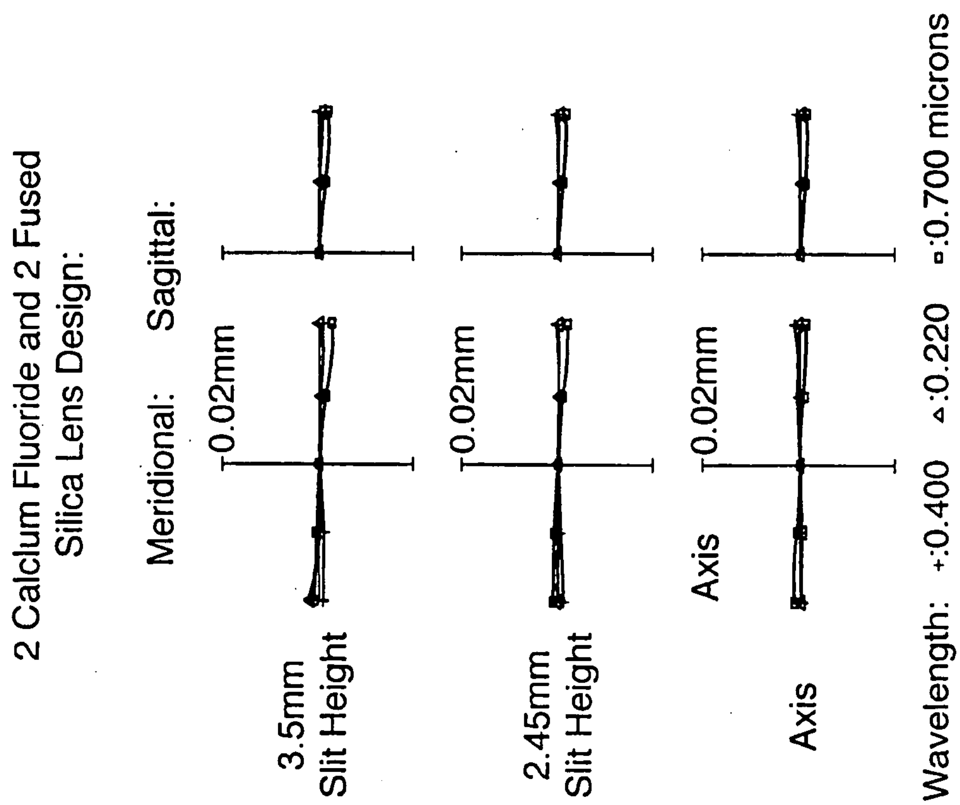


Fig.13.

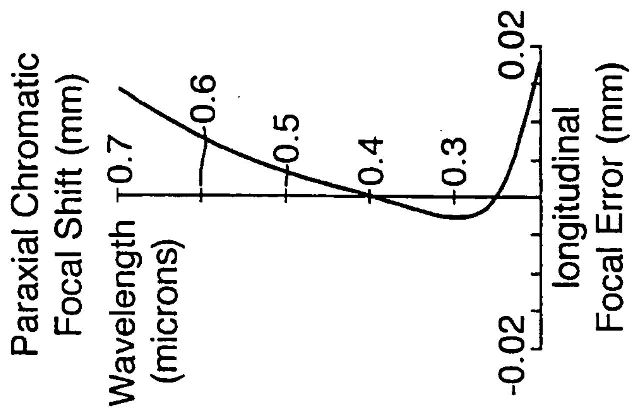


Fig.14(a).

Slit Centre

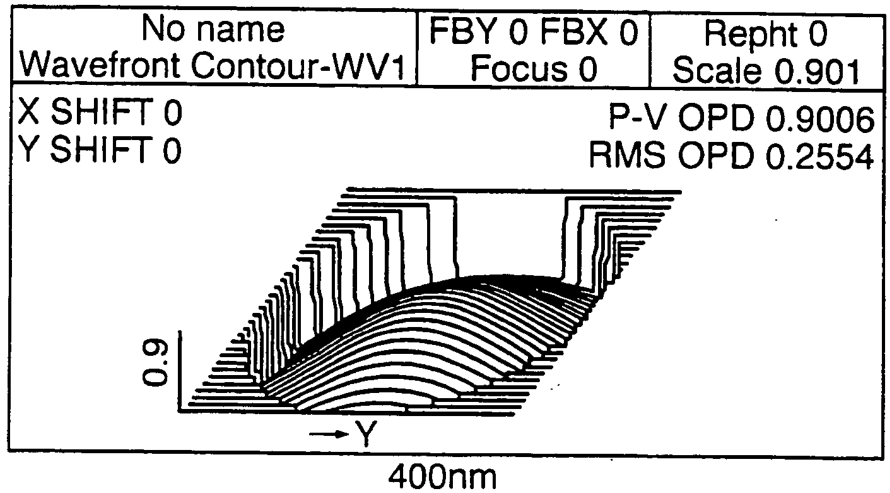


Fig.14(b).

Slit Centre

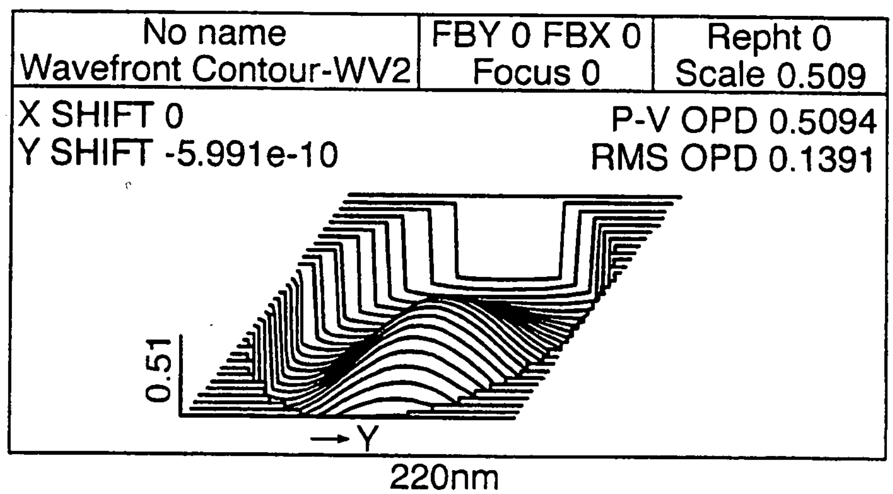


Fig.14(c).

Slit Centre

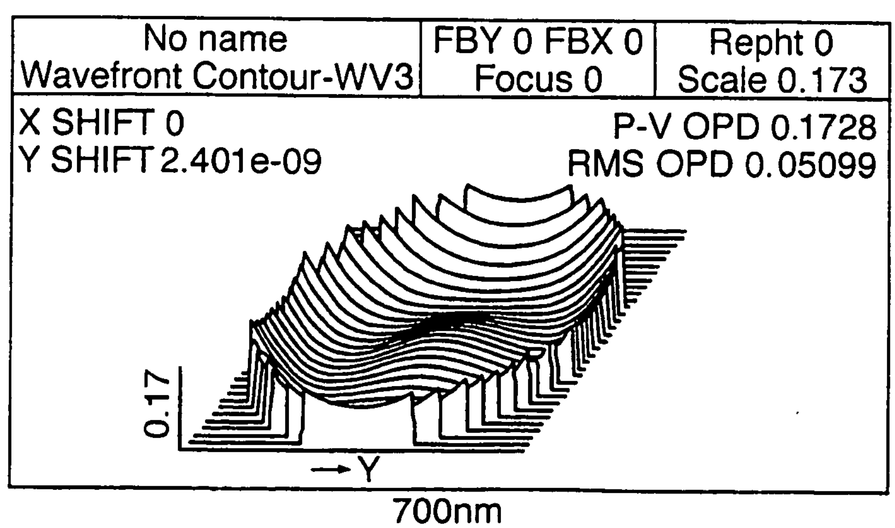
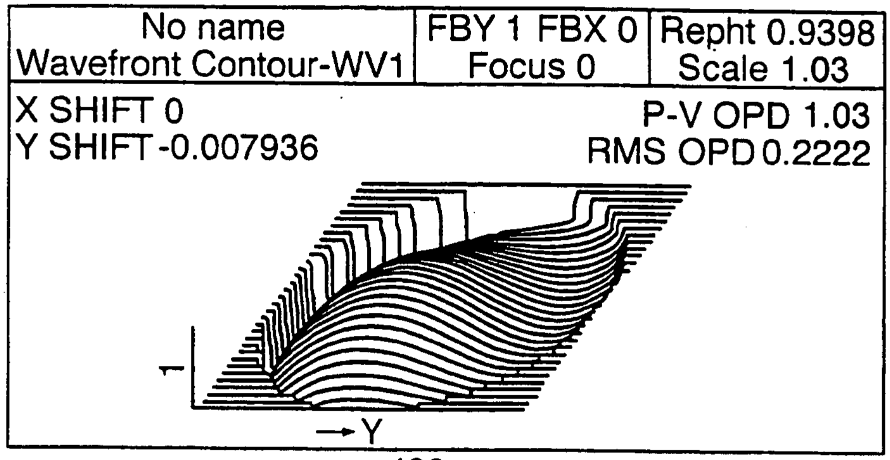


Fig.14(d).

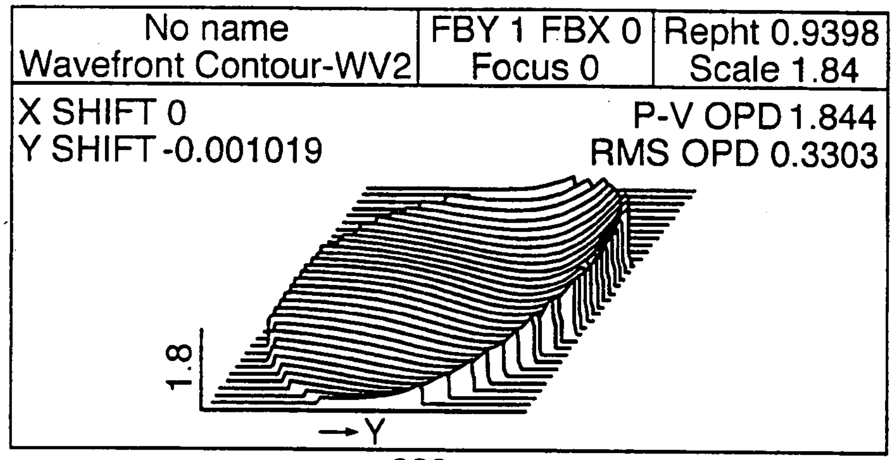
Full Slit Height



400nm

Fig.14(e).

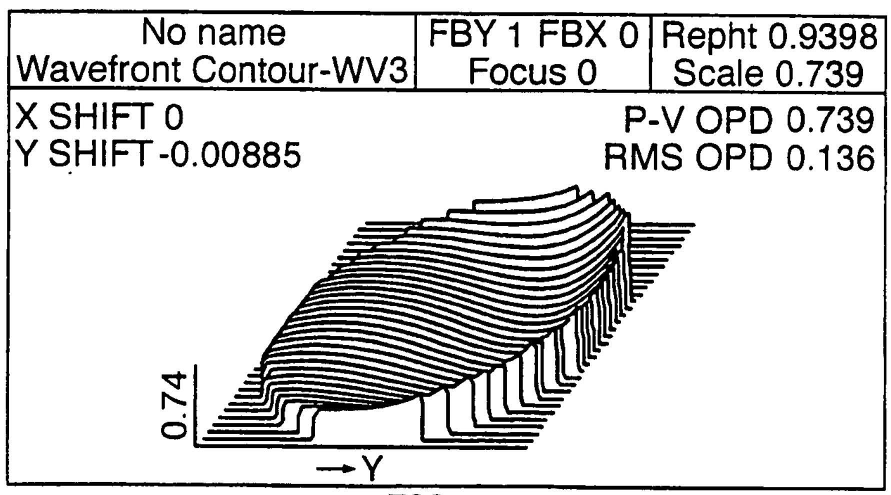
Full Slit Height



220nm

Fig.14(f).

Full Slit Height



700nm

Fig.15(b).

1 Degree Tilt

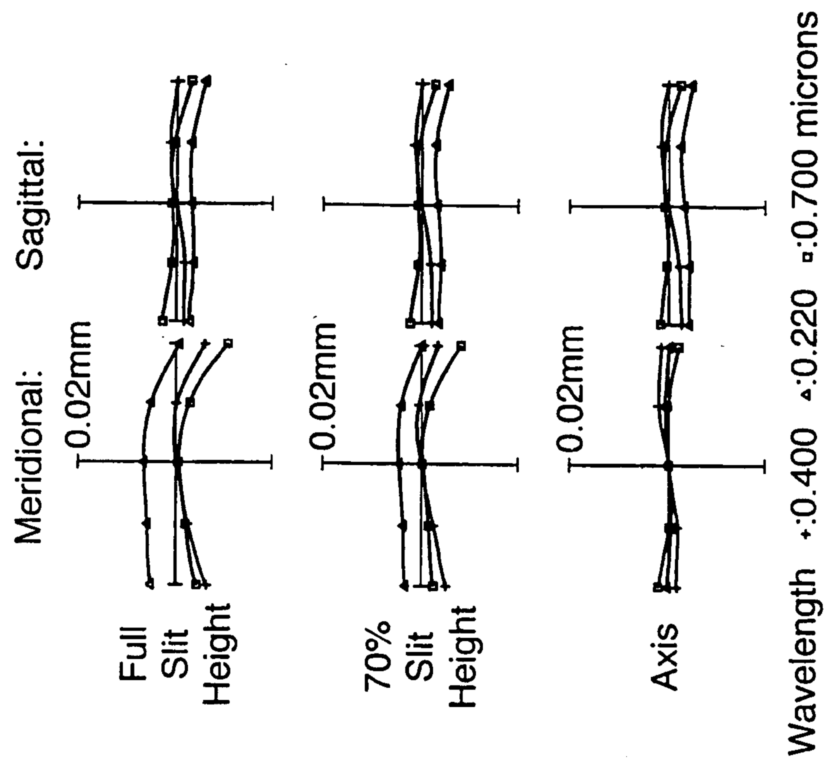


Fig.15(a).

No Tilt

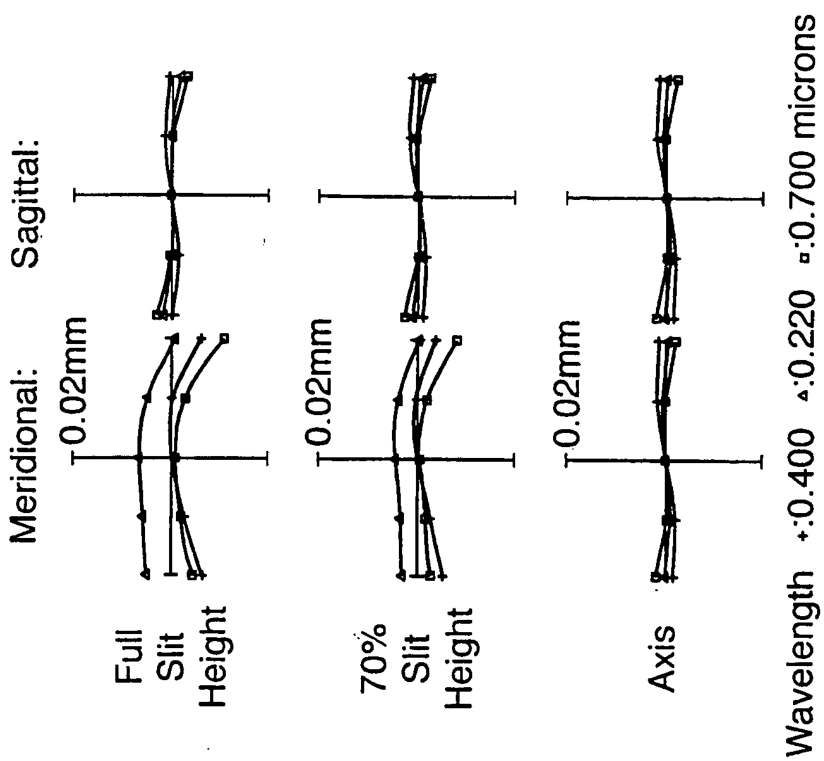


Fig.15(c).

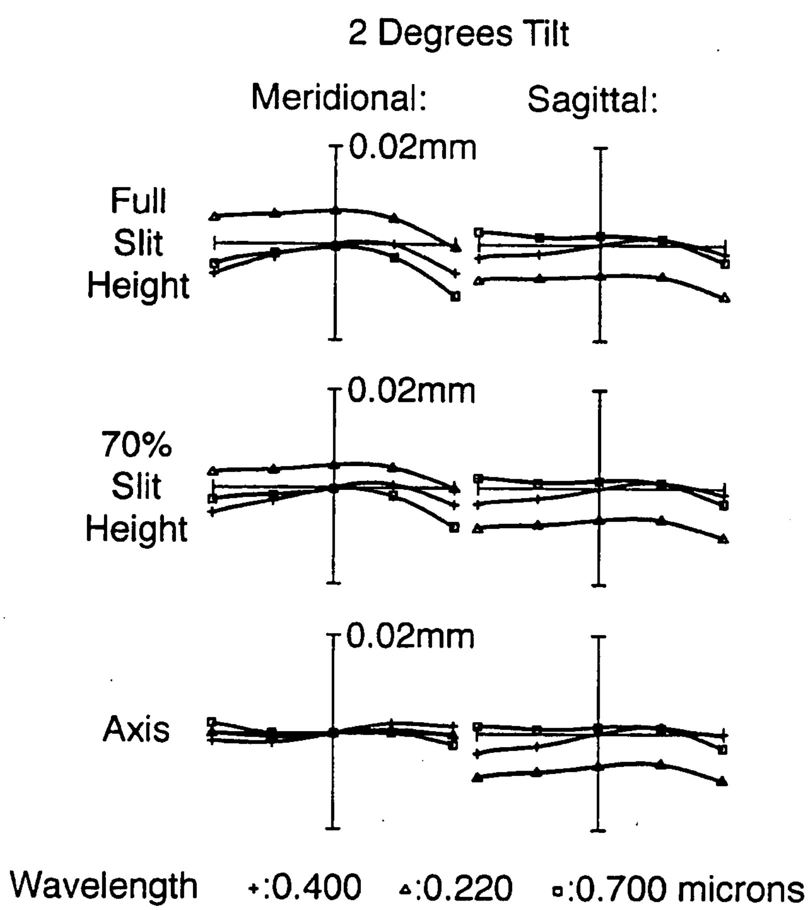

2 Degrees Tilt
Meridional:
Sagittal:
0.02mm
Full Slit Height
0.02mm
70% Slit Height
0.02mm
Axis
Wavelength +:0.400 △:0.220 □:0.700 microns

Fig.16.

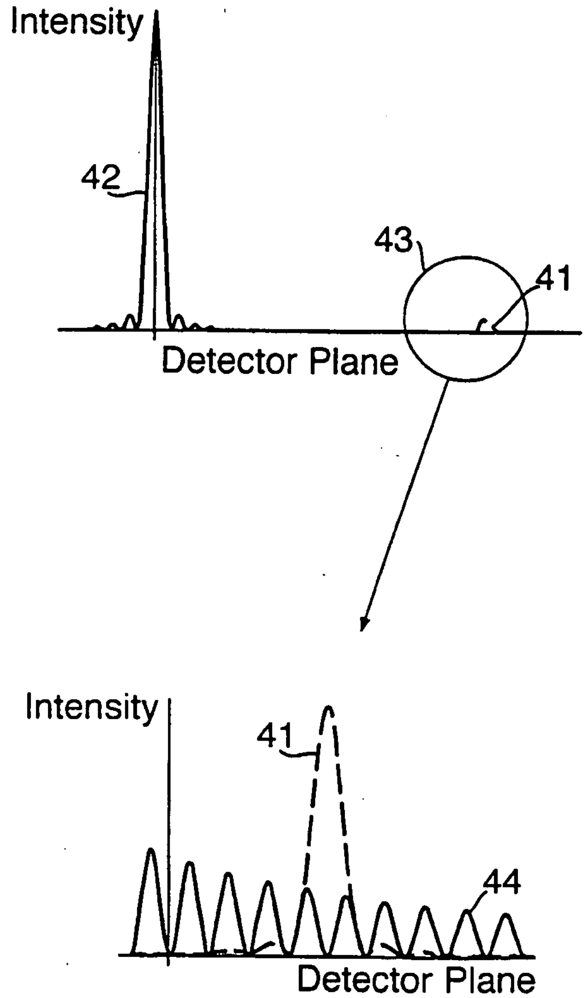

Intensity
42
43
41
Detector Plane
Intensity
41
44
Detector Plane

Fig.17(a). Laser Focus:

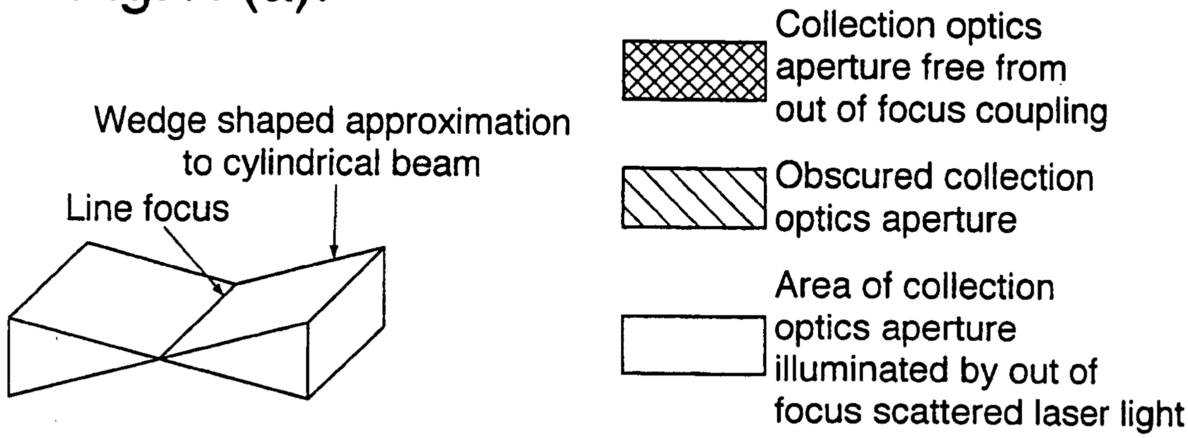


Fig.17(b). Collection optics focus with circular obscuration:

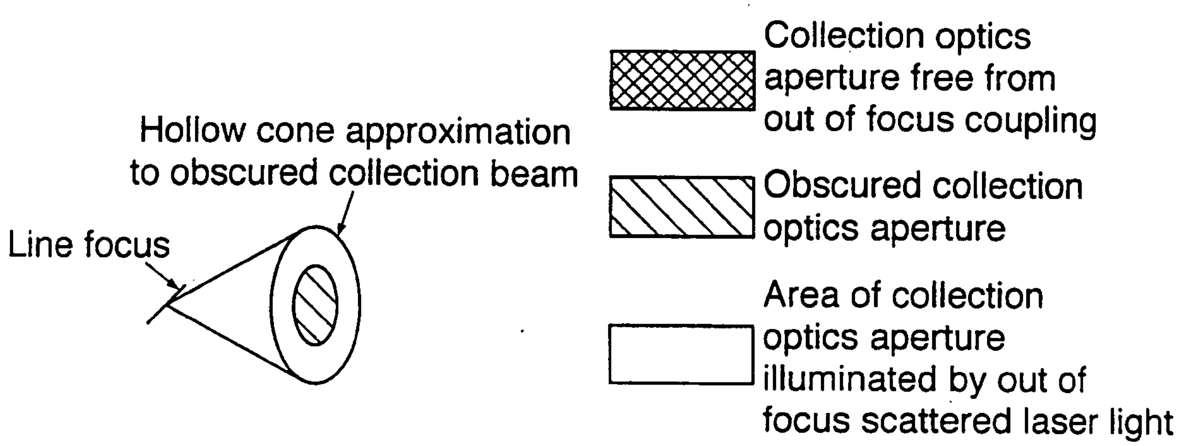


Fig.17(c). Coupling of scattered laser light into collection optics:

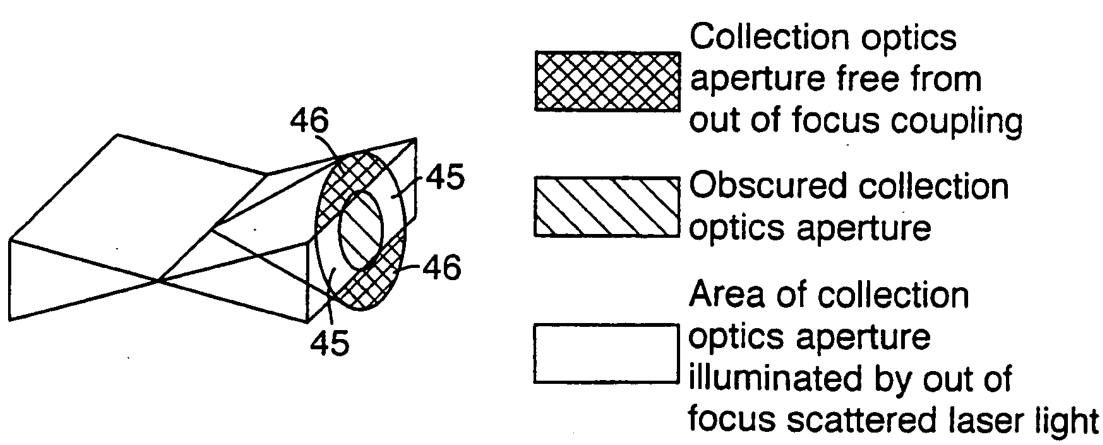
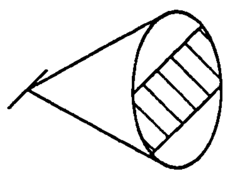


Fig.17(d).

Collection optics focus with rectangular obscuration:



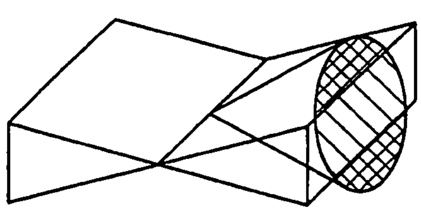
Collection optics aperture free from out of focus coupling

Obscured collection optics aperture

Area of collection optics aperture illuminated by out of focus scattered laser light

Fig.17(e).

Coupling of scattered laser light into collection optics:



Collection optics aperture free from out of focus coupling

Obscured collection optics aperture

Area of collection optics aperture illuminated by out of focus scattered laser light

INTERNATIONAL SEARCH REPORT

Int. :ional Application No
PCT/GB 00/04918

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01J3/02 G02B17/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01J G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 493 443 A (SIMON ARNO ET AL) 20 February 1996 (1996-02-20) cited in the application abstract	1
A	WO 99 08134 A (KLA TENCOR INC) 18 February 1999 (1999-02-18) cited in the application abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 March 2001	03/04/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	De Buyzer, H

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 00/04918

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5493443 A	20-02-1996	DE 4243144 A	23-06-1994
WO 9908134 A	18-02-1999	US 5999310 A	07-12-1999
		AU 9016798 A	01-03-1999
		EP 1000371 A	17-05-2000
		US 6064517 A	16-05-2000